DEVELOPING AN OBJECTIVE FUNCTION AND COST EQUATIONS FOR EX SITU TREATMENT TECHNOLOGIES

BY

MACHELLE ANN VIEUX

July 21, 1999

SPECIAL PROJECT

Advisor:
Dr. Barbara Minsker
Environmental Engineering and Science
Department of Civil and Environmental Engineering
University of Illinois at Urbana-Champaign

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

1. Introduction and Objectives

Remediation of contaminated groundwater has historically been a costly venture that takes several years or decades to achieve cleanup goals. The enormous costs associated with groundwater cleanup have initiated much research into methods of minimizing cost. To reduce the overall cost of remediation, managers must consider the entire treatment train in terms of capital and operations and maintenance (O & M) costs (Culver and Shoemaker, 1997).

Pump-and-treat systems are one of the most widely used technologies at contaminated groundwater sites (U.S. EPA, 1996). Conventional pump-and-treat systems serve two main purposes: to contain the contaminant plume by changing the natural hydraulic gradient and to remove contaminants from the groundwater aquifer. Despite being heavily criticized for being costly, lengthy, and only somewhat effective as a stand-alone technology, pump-and-treat is the most effective method to contain a contaminated groundwater plume (U.S. EPA, 1997). Thus, it continues to be an integral part of the overall clean-up strategy. When combined in a treatment train with ex situ groundwater treatment and in situ bioremediation, the system can be effective in reducing groundwater contaminants and restoring aquifer quality.

Contaminant levels may remain above desired clean-up goals for several years because of sorption and desorption into and out of aquifer material (Freeze and Cherry, 1979). The slow release of contaminants out of saturated soils and sediments results in a "tailing" of contaminant concentrations over time and space, increasing the duration of treatment. Consequently, changing groundwater flow patterns and controlling migration of contaminants have long life cycle operation and maintenance (O & M) costs. In a treatment train that begins with groundwater pumping wells, attention must be given to the post-pumping, above ground treatment cost. With sorption and desorption leading to long remediation periods, a large portion

of the overall cost for a groundwater treatment train often depends on the selection of ex situ technology.

The intent of this project is to develop an objective function to minimize the cost of ex situ groundwater treatment. Five contaminant classes are considered: Volatile Organic Compounds (VOC), Semi-Volatile Organic Compounds (SVOC), fuels, ordnance, and metals. Appendix A provides a list of typical contaminants for each class. For each contaminant class, equations representing the capital and O & M costs for ex situ technologies are presented. The cost of discharging treated water to a publicly owned treatment works (POTW) is also included. Costs associated with monitoring wells, injection/extraction wells, and subsurface treatment/enhancement are not a part of the project scope.

After extraction, groundwater can be treated to remove dissolved contaminants using a variety of ex situ technologies. Physical processes that remove contaminants from groundwater include air stripping, coagulation/flocculation, filtration, precipitation, and carbon adsorption. Chemical processes that transform contaminants include ultraviolet (UV), ozone, and hydrogen peroxide systems. The UV/ozone/hydrogen peroxide treatments are collectively called Advanced Oxidation Processes (AOP). Biological processes include ex situ bioreactors that rely on microbial activity to destroy contaminants. The selection of applicable remediation technologies for each contaminant class is based on "better" or "average" rating codes given by the Federal Remediation Technologies Roundtable (1997). This project will not evaluate the effectiveness of each treatment technology. Cost of ex situ treatment will be the only evaluation factor. Table 1 lists the remediation technologies considered for each contaminant class.

Table 1. Applicable Remediation Technologies for Contaminant Classes

	VOC	SVOC	Fuels	Ordnance	Metals
Air Stripping	X	X	X		
Carbon Adsorption using granular activated carbon (GAC)	X	X	X	X	
Bioreactor	X	X	X	X	
Advanced Oxidation Processes (AOP)	X	X	X	X	
Coagulation/Flocculation					X
Precipitation					X
Media Filtration	X	X	X	X	X

2. Methodology

2.1 Overview

The cost data for each treatment technology were obtained from Remedial Action Cost Engineering and Requirements (RACER), a parametric cost modeling system. RACER uses a cost database from Environmental Cost Handling Options and Solutions developed by the R.S. Means Company and Talisman Partners, Ltd. The database includes material, equipment, and labor costs for several remediation technologies. Although RACER accounts for prime and sub contractor overhead, risk, and profit, these factors are site specific and are therefore excluded from the general cost evaluation in this project. For all technologies, RACER applies a default electricity rate of $0.06 per kilowatt-hour (KWH). The influent flow rate is assumed constant over time, with the treatment facility operating 97% of the time during any given year.

For each of the treatment technologies, RACER requires the user to input the influent flow rate and safety level. The safety level refers to four different levels, A, B, C, and D, as defined by OSHA 29 CFR Part 1910. Each level specifies a certain amount and type of Personal Protective Equipment (PPE) required for on-site workers. Level "A" is the most protective and "D" is the least protective. A change in safety level can significantly affect the capital and O & M costs. To maintain simplicity and consistency, safety level D was assumed for all contaminant classes. Safety level D includes disposable latex gloves and coveralls as part of the O & M costs. Higher levels of protection include the cost of latex gloves, coveralls, and respirator cartridges. As part of the capital cost, RACER includes the mandatory OSHA Operator Health and Safety Course. The items included in the capital costs are the same for every safety level, but the quantities, labor costs, labor hours and some equipment costs increase for the more protective safety levels.

The influent flow rate, measured in gallons per minute (gpm) determines the size of the system and the level of maintenance required. For each technology, the influent flow rate was varied to obtain a data set of present value capital and O & M costs. Using the influent flow rate as an independent variable, regression techniques were used to develop cost functions representing the present value capital and annual O& M cost for a particular ex situ technology and contaminant class.

2.2 Description of Technologies and Related Parameters

Within RACER, each technology has a set of required primary and secondary parameters that the user must input. The following sections specify the default parameters and assumptions.

2.2.1 Air Stripping

Air stripping makes use of contaminant volatility to transfer VOCs, SVOCs, and fuels from the liquid phase to the vapor phase. Two standard configurations selected for cost evaluation are the packed tower (range of influent flow 10 to 2250 gpm) and low profile tray stack (range of influent flow 1 to 750 gpm). For each configuration, the contaminant volatility must be entered. Table 2 lists the volatility classification for common contaminants.

Table 2. **Air Stripping: Volatility Classification for Common Contaminants**

Very High Carbon tetrachloride Tetrachloroethylene	**High** 1,1-Dichloroethylene Vinyl chloride 1,1,1-Trichloroethane Trichloroethylene
Moderate cis-1,2-Dichloroethylene trans 1,2-Dichloroethylene 1,1-Dichloroethane Chloromethane Chloroethane Benzene Ethylbenzene Toluene Xylenes (total) Chlorobenzene Chloroform 1,3-Dichlorobenzene 1,2-Dichlorobenzene 1,2-Dichloropropane Methylene Chloride Bromobenzene	**Low** Naphthalene 1,2-Dichloroethane 1,1,2-Trichloroethane 1,2-Dibromoethane 1,1,2,2-Tetrachloroethane Ethylene dibromide Methyl tert butyl ether (MTBE)

The volatility classification assumed for VOCs is high. Fuels and SVOC were assumed to have moderate volatility. Another required primary parameter, the removal percentage, was assumed to be 99% for all contaminant classes. The secondary parameters included the packed tower diameter, packed tower height, low profile tray stack number of trays, and number of strippers. For the secondary parameters, RACER automatically calculates default values based on the selection of primary parameters. Although volatilized off-gases may sometimes require treatment, such treatment is not included in this project.

2.2.2 Carbon Adsorption Using Granular Activated Carbon (GAC)

Carbon adsorption transfers the contaminant from the liquid groundwater media to the adsorbent, which is commonly GAC. The GAC's effectiveness may be hindered by the presence

of other constituents; hence, the concentrations for oil, grease, and dissolved inorganics were assumed less than 10 parts per million (ppm), with suspended solids less than 50 ppm. The O & M estimation in RACER includes the removal, transport, and regeneration/disposal of spent carbon. When used to remove ordnance, the GAC cannot be regenerated. Three types of carbon adsorption systems are available: dual bed, modular permanent, and modular disposable. The dual bed has two carbon adsorbers that can be arranged in series or parallel. The modular permanent uses one adsorber that can be regenerated after the carbon is spent. The modular disposable system consists of one adsorber that is disposed after the carbon is spent. The range of influent flow for a dual bed system is 1 to 2000 gpm and 1 to 200 gpm for modular (permanent and disposable) systems. Each system requires the redundancy type to be specified. The choices are either single pass redundancy or two in series. The concentration of organics can affect the frequency of disposal, replacement, or regeneration, thereby affecting O & M costs. The total organic carbon (TOC) content of the fluid to be treated is assumed to be 5 ppm.

2.2.3 Bioreactors

Bioreactors, as defined by RACER, only utilize aerobic degradation of contaminants by microorganisms. The assumed end products are carbon dioxide, water, and cells. In addition to influent flow rate and safety level, Chemical Oxygen Demand (COD) is a required parameter for estimating the costs of a bioreactor. Both the influent flow rate (range 1 to 100 gpm) and the COD were varied (range 50 to 1000 ppm), and the resulting costs recorded. A heat exchanger to maintain temperatures for microbial activity is automatically sized based on influent flow rate. Several secondary parameters remain at default values; no pH adjustment, reagent, or additive is considered, the influent water temperature is 55^0 F, and the process water temperature is 80^0 F.

Based on the default values, one boiler is in operation with a capacity of 960 million British Thermal Units.

2.2.4 Advanced Oxidation Processes (AOP)

The basic principle underlying AOP systems is transforming contaminants by utilizing hydroxyl radicals. Hydroxyl radicals created by reactions between ozone and hydrogen peroxide, in the presence and absence of UV light, can oxidize contaminants to harmless end products, such as carbon dioxide, water, and salts. The AOP systems available in RACER are the high intensity ultraviolet/hydrogen peroxide (UV/peroxide) system and low intensity ultraviolet/ozone/hydrogen peroxide (UV/ozone/peroxide) system. The specific contaminant selection determines the default type of oxidation system, UV/peroxide or UV/ozone/peroxide. Influent concentration is required only for contaminants that can be treated by UV/peroxide, with a valid range of 0.01 to 1000 milligrams per liter (mg/L). Effluent concentration is required only for contaminants that can be treated by UV/peroxide, with a valid range of 0.001 to 100 mg/L. Table 3, lists the contaminants and the selection of effluent concentration.

Table 3. Specific Contaminants and Effluent Limits for AOP

Contaminant	Effluent Limit (mg/L)	Source for Effluent Limit
1,1,2,2 Tetrachloroethane	Not required	
1,1 Dichloroethane	0.005	Based on limits for 1,2 Dichloroethane
1,1 Dichloroethylene	0.007	(1)
1,2 Dichloroethane	Not required	
1,4 Dioxan	0.003	(1)
cis-1,2 Dichloroethylene	Not required	
trans 1,2 Dichloroethane	Not required	
Benzene	0.005	(1)
Carbon Tetrachloride	Not required	
Chlorobenzene	0.1	(1) Based on limits for monochlorobenzene
DNT	Not required	
Ethylbenzene	Not required	
HMX	Not required	
MTBE	0.02	(3) No Federal Standard
Nitrobenzene	Not required	
PAHs	Not required	
Perchloroethylene	0.005	(1)
Phenol	0.005	Based on typical clean-up goals for fuels
RDX	0.02	(2) No Federal Standard
Toluene	1	(1)
Trichloroethane	0.005	(1) Based on limits for 1,1,2-Trichloroethane
Trichloroethylene	0.005	(1)
Trinitrotoluene	0.02	(2) No Federal Standard
Xylene	10	(1)
Vinyl Chloride	0.002	(1)

(1) Safe Drinking Water Act Amendments of 1996
(2) EPA-822-B-96-002, Drinking Water Regulations and Health Advisories, October 1996
(3) EPA-822-F-97-009, Drinking Water Advisory: Consumer Acceptability Advice and Health Effect Analysis on Methyl-Tertiary-Butyl Ether (MTBE), December 1997

2.2.5 Coagulation/Flocculation

Coagulation uses electrolytes in solution to reduce electrical repulsive forces on particle surfaces. Flocculation forms larger aggregates from fine particles and/or colloids by chemical bridging. The larger particles are settled out of the liquid media and can be removed. The valid range for influent flow is 1 to 1645 gpm. The Secondary parameters include influent piping length, effluent piping length, and pipe material. The default influent and effluent piping length is 100 feet. The default piping material is PVC.

2.2.6 Metal Precipitation

Metal precipitation transforms a metallic ion into an insoluble precipitate that can be removed from liquid media. The influent flow range for metals precipitation is 1 to 100 gpm. The metals concentration, influent pH, and effluent pH are required primary parameters. The influent pH and metal concentrations are varied with the influent flow rate, while the effluent pH is assumed to be 7. The maximum metal concentration is 1000 mg/L. Secondary parameters of influent total suspended solids (TSS) and other precipitating anions/cations remain at default values. The default TSS concentration is equal to 10% of the influent metals concentration. The concentration of other precipitating anions/cations is a default value equal to the metal concentration.

2.2.7 Media Filtration

Media filtration removes suspended solids or contaminants from an aqueous waste stream by forcing the fluid through a porous medium. Filtration uses granular and cartridge filter to physically remove particles, but does not capture dissolved contaminants. Media filtration is commonly used in a treatment train to remove larger particles prior to another technology or as a polishing step before exiting the treatment system. Therefore, it will not be considered as a stand-alone technology. The costs are listed to aid in consideration of a treatment train. Applications for granular media include removal of solids after clarification following precipitation and coagulation reactions; removal of residual biological floc from secondary treatment; and pretreatment for protection of air strippers, ion exchange systems, and other treatment processes. Secondary parameters include filtration rate (default 5 gpm/sf), number of units (default 2), influent/effluent piping length (default 100 ft), and piping material (default PVC).

2.2.8 Discharge to POTW

After treatment, the groundwater may be discharged to a POTW. The POTW is assumed to be located off-site and the distance to the sewer line connection is 50 feet. Other assumptions include: the connection fee is $1000, the wastewater disposal fee is $2 per thousand gallons, the discharge operates for 20 hours per day, and the flow rate (gpm) equals the treatment facility influent flow rate.

3. Results and Discussion

The objective is to minimize the total cost of ex situ groundwater treatment.

Minimize $C^{TOT} = c_{j\,k}{}^{cap} + c^{cap,\,POTW} + [c_{j\,k}{}^{op} + (c^{ana,\,water})f + (c^{ana,gas})g + c^{op,\,POTW}]\,(P\,|\,A, i, n)$

Where

C^{TOT} = total present value ex situ treatment cost

$c_{j\,k}{}^{cap}$ = capital cost for technology j of contaminant class k ($)

$c_{j\,k}{}^{op}$ = annual O & M cost for technology j of contaminant class k ($/year)

$c^{ana,\,water}$ = annual cost of collecting, testing and analyzing groundwater samples for contaminant class k ($/test)

$c^{ana,\,gas}$ = annual cost of collecting, testing and analyzing off-gas samples for technology j of contaminant class k ($/test)

$c^{cap,\,POTW}$ = capital cost of disposing treated groundwater to a POTW ($)

$c^{op,\,POTW}$ = annual O & M cost of disposing treated groundwater to POTW ($)

n = duration of O & M (years)

f = number of groundwater tests per year

g = number of off-gas tests per year

j = 1,2, ….m ex situ technologies

k = 1, 2, 3, 4, 5 contaminant class

i = interest rate

(P | A, i, n) = financial factor for converting a series of n O & M payments to present worth

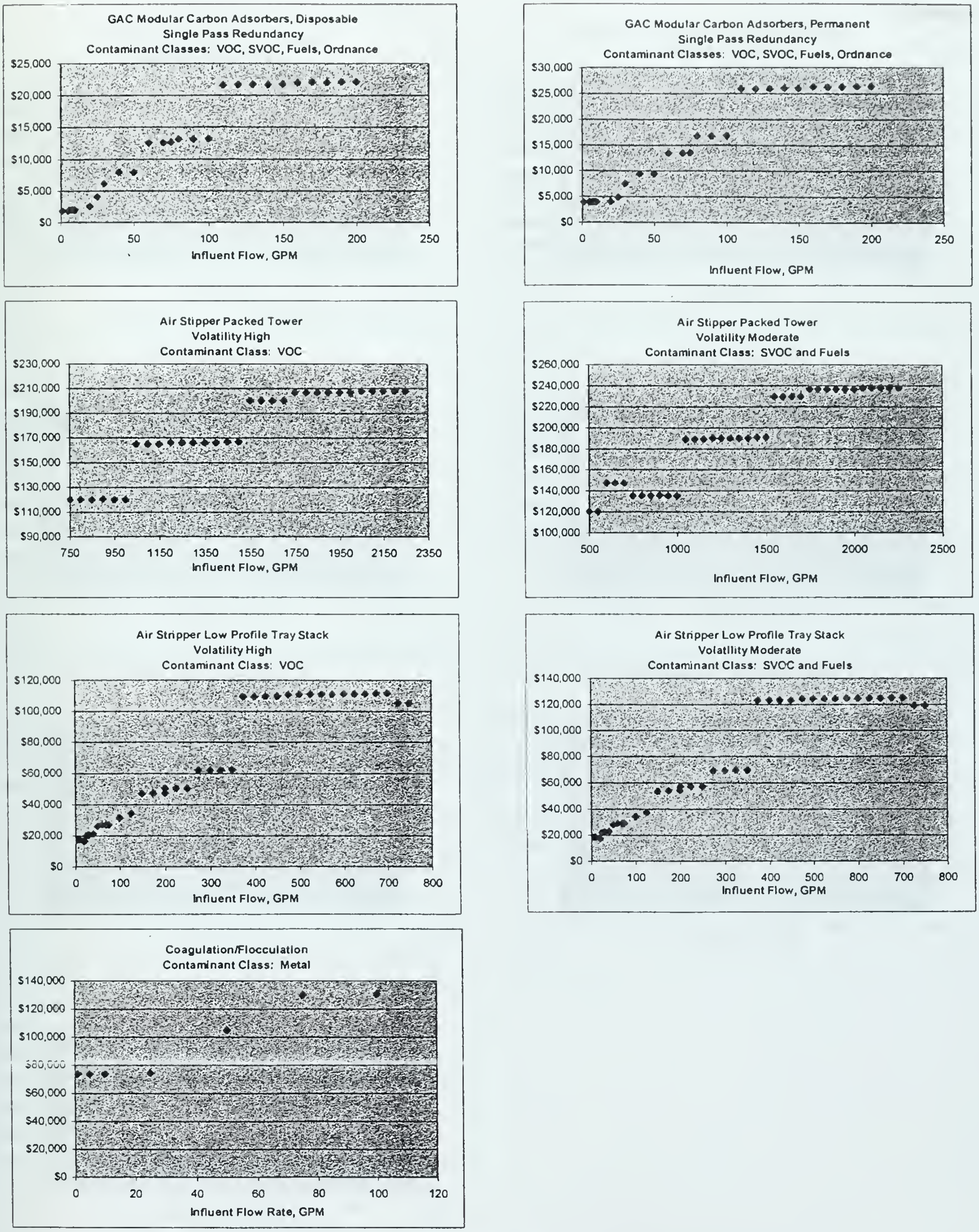

Figure 1. Capital cost versus influent flow rate, GPM for various ex situ treatment technologies Trendlines and R^2 values shown.

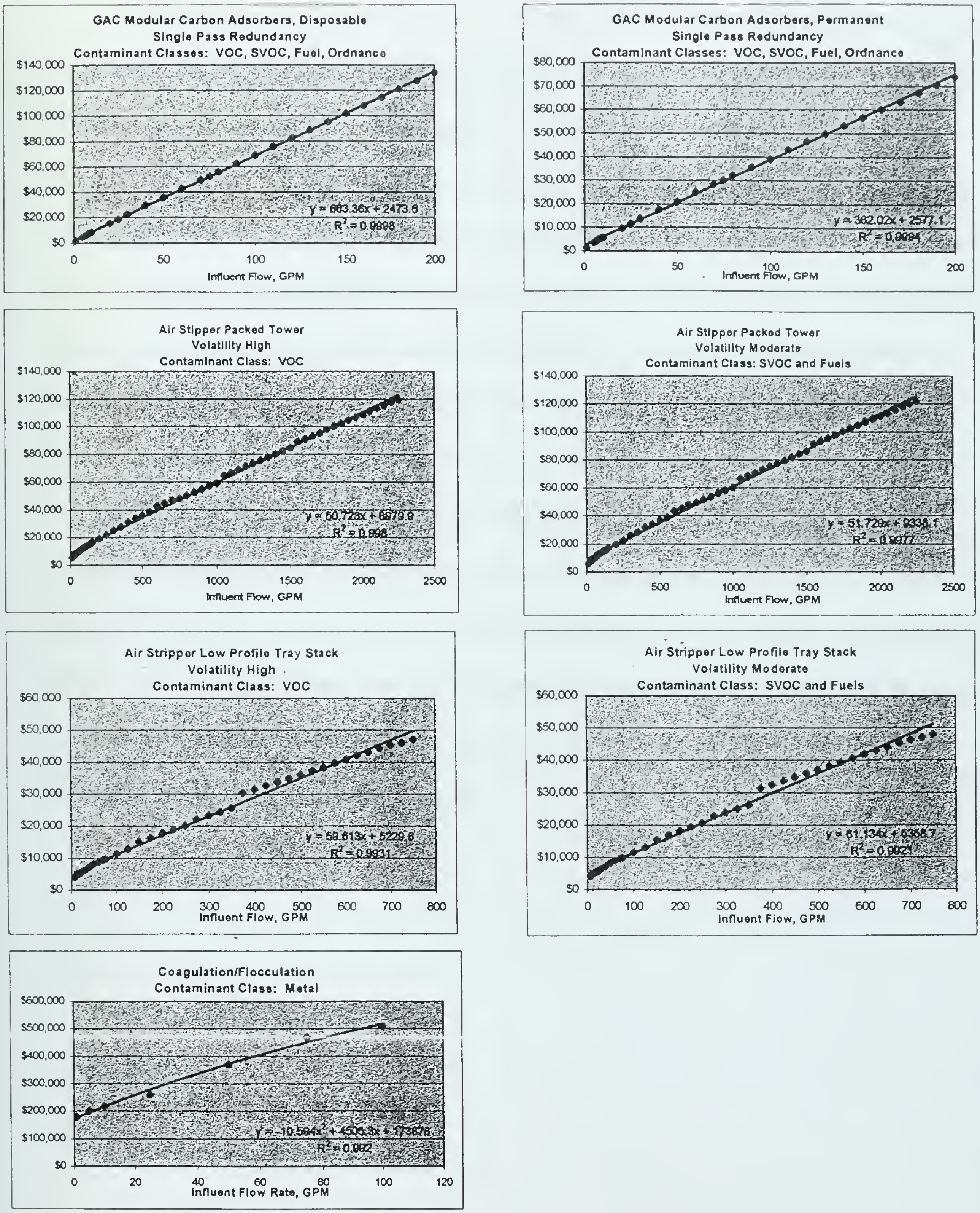

Figure 2. O & M Cost for a typical 12 month period versus influent flow rate, GPM for various ex situ treatment technologies. Trendlines and R^2 values shown.

The values for c_{jk}^{cap} are constant within a certain flow range and are a function of contaminant class and treatment technology. Figure 1 shows that capital costs do not increase linearly with influent flow rates. The capital cost function is discontinuous, reflecting that a treatment facility can handle a range of influent flows for a fixed cost. Note however, that the capital costs are fixed over a narrow range of influent flows before stepping up to the next cost level. The range and costs differ for each technology and are detailed in Table 4. Although the capital cost is a fixed value, it is a function of contaminant class and flow range. One basic assumption of this project is that the influent flow rate from a pump-and-treat system will be known. Given the influent flow rate, values for c_{jk}^{cap} can be assigned using Table 4.

In contrast, Figure 2 shows linear O & M costs for all ex situ technologies except coagulation/flocculation. The R^2 values for all functions are greater than 0.99. c_{jk}^{op} is also a function of contaminant class and treatment technology and can be represented by the equations listed in Table 5. Appendices B through F summarize the capital, O & M (total for a 15 year duration), total (capital plus O & M), and annual O & M costs for each technology and configuration of required primary parameters.

Table 4. Equations for c_{jk}^{cap}

Contaminant Class and Technology Configuration	Flow Range (gpm)	c_{jk}^{cap} ($)
VOCs		
Air Stripper Packed Tower - Volatility high	10 to 30	35,354
	31 to 60	41,851
	61 to 100	58,313
	101 to 140	62,788
	141 to 250	73,439
	251 to 350	89,510
	351 to 550	108,725
	551 to 700	132,465
	701 to 1000	120,286
	1001 to 1500	165,918
	1501 to 1700	200,198
	1701 to 2250	207,558
Air Stripper Low Profile Tray Stack - Volatility high	less than 20	16,962
	20 to 50	20,611
	51 to 75	26,636
	76 to 125	32,684
	126 to 200	47,152
	201 to 250	50,418
	251 to 350	62,118
	351 to 750	110,181
Modular Carbon Adsorbers, Permanent - Single Pass Redundancy	less than 10	3,928
	11 to 25	4,489
	26 to 50	8,807
	51 to 75	13,475
	76 to 100	16,787
	101 to 200	26,158
Modular Carbon Adsorbers, Disposable - Single Pass Redundancy	less than 5	1,811
	6 to 20	2,011
	21 to 50	6,503
	51 to 100	12,875
	101 to 200	21,904

Contaminant Class and Technology Configuration	Flow Range (gpm)	$c_{j\,k}^{cap}$ ($)
SVOCs and Fuels		
Air Stripper Packed Tower - Volatility moderate	10 to 25	37,681
	26 to 60	44,045
	61 to 140	66,526
	141 to 200	78,909
	201 to 350	94,542
	351 to 550	120,107
	551 to 700	147,630
	701 to 1000	135,451
	1001 to 1500	189,839
	1501 to 1700	229,909
	1701 to 2250	237,269
Air Stripper Low Profile Tray Stack - Volatility moderate	less than 20	17,956
	21 to 40	22,344
	41 to 75	18,836
	76 to 125	35,884
	126 to 250	55,485
	251 to 350	69,418
	351 to 750	123,847
Modular Carbon Adsorbers, Permanent - Single Pass Redundancy	less than 10	3,928
	11 to 25	4,489
	26 to 50	8,807
	51 to 75	13,475
	76 to 100	16,787
	101 to 200	26,158
Modular Carbon Adsorbers, Disposable - Single Pass Redundancy	less than 5	1,811
	6 to 20	2,011
	21 to 50	6,503
	51 to 100	12,875
	101 to 200	21,904
Metals		
Coagulation/Flocculation where q is influent flow rate ($R^2 = 0.9829$)	$c_{j\,k}^{cap} = -0.0822\ q^2 + 377.54\ q + 84324$	

Contaminant Class and Technology Configuration	Flow Range (gpm)	c_{jk}^{cap} (\$)
Ordnance		
Modular Carbon Adsorbers, Permanent - Single Pass Redundancy	less than 10	3,928
	11 to 25	4,489
	26 to 50	8,807
	51 to 75	13,475
	76 to 100	16,787
	101 to 200	26,158
Modular Carbon Adsorbers, Disposable - Single Pass Redundancy	less than 5	1,811
	6 to 20	2,011
	21 to 50	6,503
	51 to 100	12,875
	101 to 200	21,904

Table 5. Equations for c_{jk}^{op}

VOC

Air Stripper Packed Tower - Volatility high

$$c_{jk}^{op} = 50.728\ q + 8979.9$$

Air Stripper Low Profile Tray Stack - Volatility high

$$c_{jk}^{op} = 59.613\ q + 5229.6$$

Modular Carbon Adsorbers, Permanent - Single Pass Redundancy

$$c_{jk}^{op} = 362.02\ q + 2577.1$$

Modular Carbon Adsorbers, Disposable - Single Pass Redundancy

$$c_{jk}^{op} = 663.36\ q + 2473.6$$

SVOC and Fuels

Air Stripping packed Tower -Volatility moderate

$$c_{jk}^{op} = 51.729\ q + 9338.1$$

Air Stripping Low Profile Tray Stack -Volatility moderate

$$c_{jk}^{op} = 61.134\ q + 5358.7$$

Modular Carbon Adsorbers, Permanent - Single Pass Redundancy

$$c_{jk}^{op} = 362.02\ q + 2577.1$$

Modular Carbon Adsorbers, Disposable - Single Pass Redundancy

$$c_{jk}^{op} = 663.36\ q + 2473.6$$

Metals

Coagulation/Flocculation

$$c_{jk}^{op} = -0.0149\ q^2 + 120.94\ q + 11304$$

Ordnance

Modular Carbon Adsorbers, Permanent - Single Pass Redundancy

$$c_{jk}^{op} = 362.02\ q + 2577.1$$

Modular Carbon Adsorbers, Disposable - Single Pass Redundancy

$$c_{jk}^{op} = 663.36\ q + 2473.6$$

where q is influent flow rate, gpm

The cost of collecting, testing, and analyzing groundwater and off-gas samples ($c^{ana,\ water}$ and $c^{ana,\ gas}$) is listed in Appendix G. Although off-gas treatment is not considered in this project, analysis is normally required. The frequency of sampling water and off-gas per year, f and g, can be input by the user or assumed to be four (quarterly sampling plan).

Similar to the treatment technologies, the cost of discharging to a POTW can be represented by capital and O & M costs. The capital costs include site preparation (clearing, grubbing, and seeding) for installation of a sewer drain line, trenching, backfill, and line connection fees. The drain system was assumed to be gravity flow through an 8-inch PVC pipe 50 feet in length, with a discharge rate equal to the influent flow rate of the treatment system. For discharge rates less than 500 gpm, the capital cost for POTW disposal ($c^{cap,\ POTW}$) is 10,315. For discharge rates greater than or equal to 500 gpm, $c^{cap,\ POTW}$ is 11,200.

The O & M cost includes the wastewater disposal fee, which was assumed to be $2.00 per thousand gallons. The equation for the O & M cost is represented by the following linear equation.

$$c^{op,\ POTW} = 517.64\ x + 2227.1$$

where x is the effluent discharge rate in gpm

A comparison of costs for all applicable technologies in each contaminant class is shown in Figures 3 through 5. Given that safety level D applies to all contaminant classes, the capital and O & M costs for a bioreactor, carbon adsorption, and media filtration are the same for VOCs, SVOCs, fuels, and ordnance (Appendices B through F). Since air stripping relies on the volatility of a contaminant, the costs are greater when treating less volatile compounds.

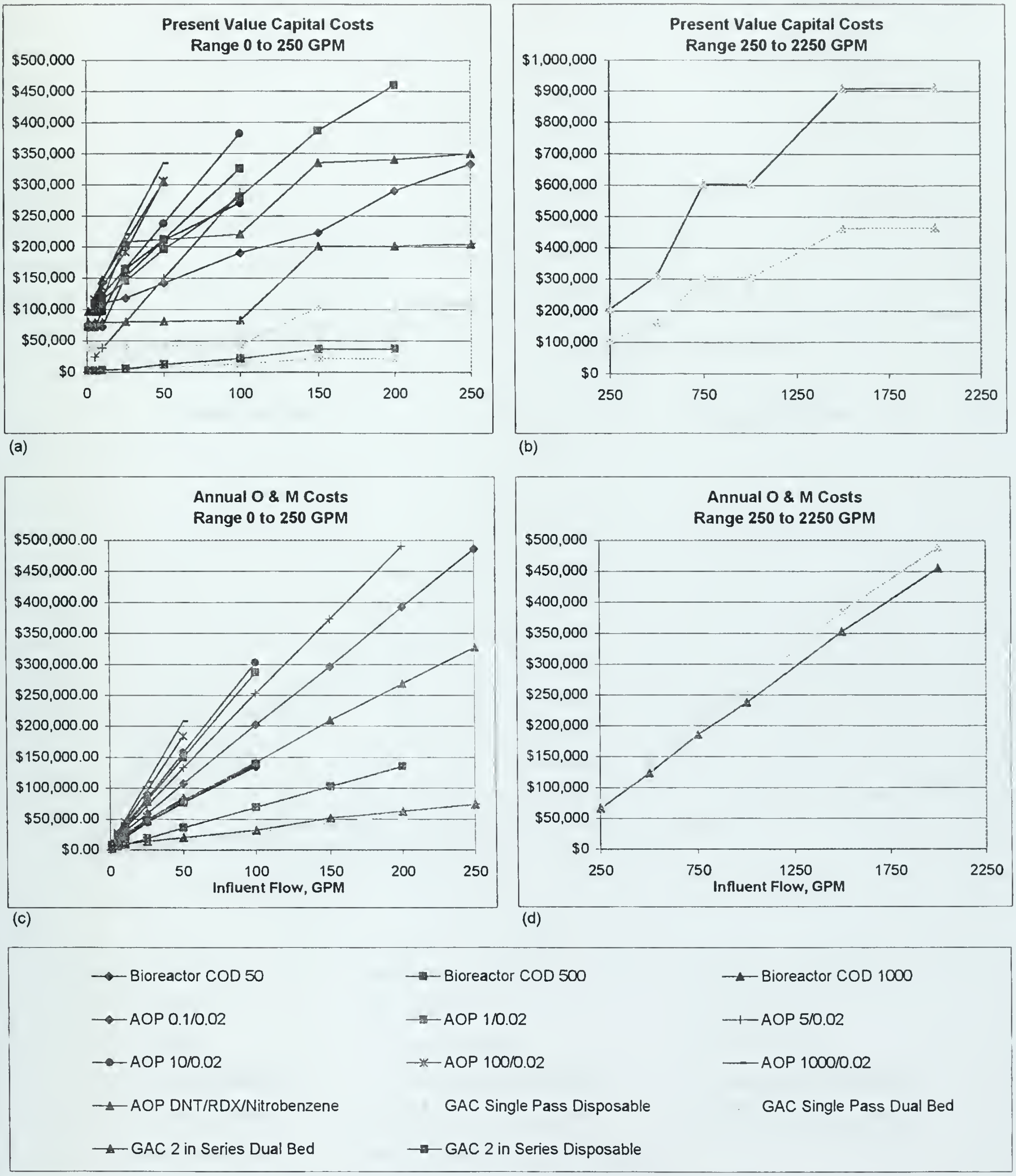

Figure (5) Cost versus influent flow for various ordnance treatment technologies.
(a) Comparison of capital costs for a range of flow between 0 and 250 GPM. (b) Comparison of capital costs for influent flow ranging from 250 to 2250 GPM. (c) Comparison of annual O & M costs for influent flow ranging from 0 to 250 GPM. (d) Comparision of annual O & M costs for technologies with influent flow ranging from 250 to 2250 gpm.

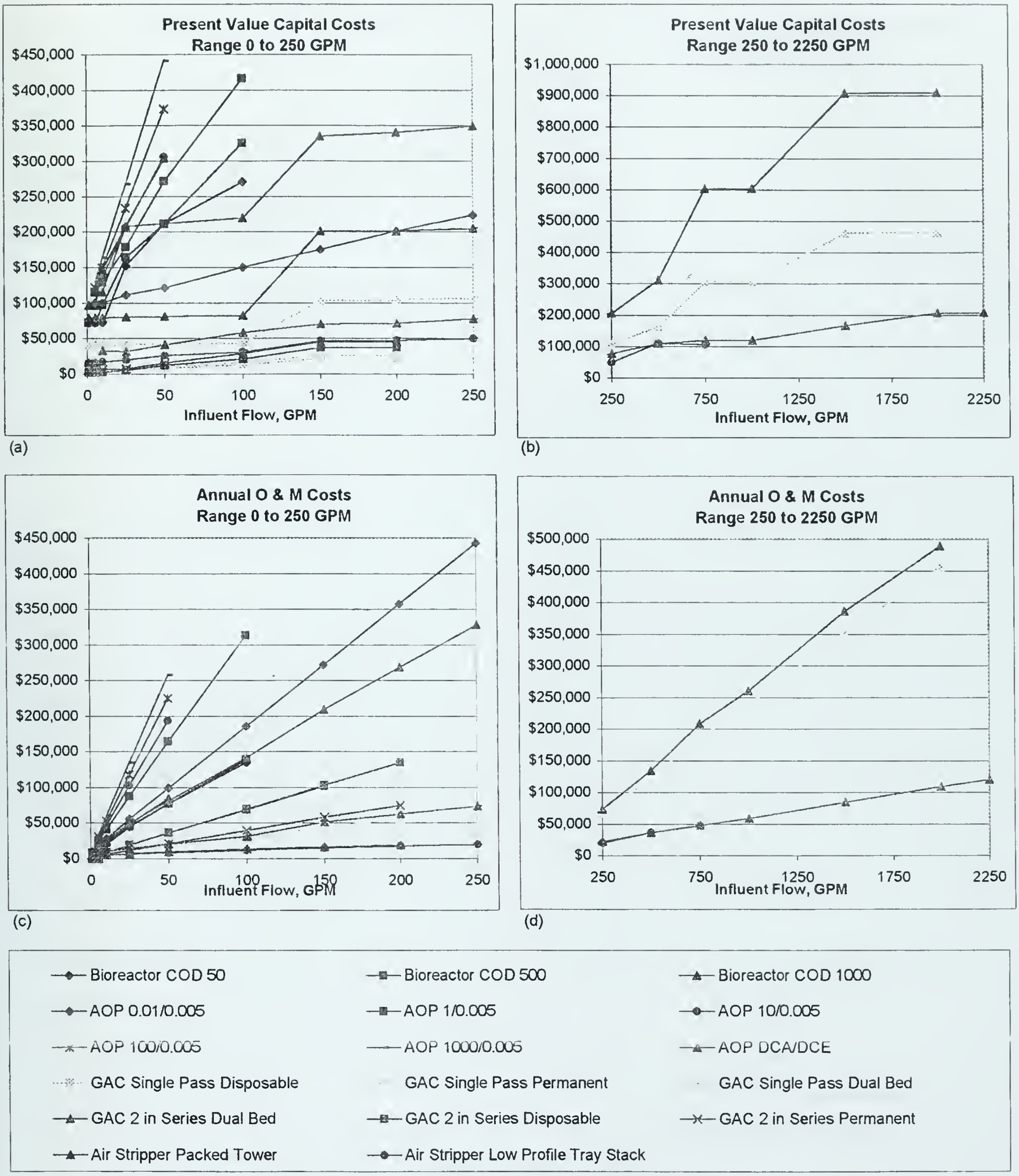

Figure (3) Cost versus influent flow for various VOC technologies. The valid range of flow varies for each technology and configuration. (a) Comparison of capital costs for a range of flow between 0 and 250 GPM. (b) Comparison of capital costs for influent flow ranging from 250 to 2250 GPM. (c) Comparison of annual O & M costs for influent flow ranging from 0 to 250 GPM. (d) Comparision of annual O & M costs for technologies with influent flow ranging from 250 to 2250 gpm.

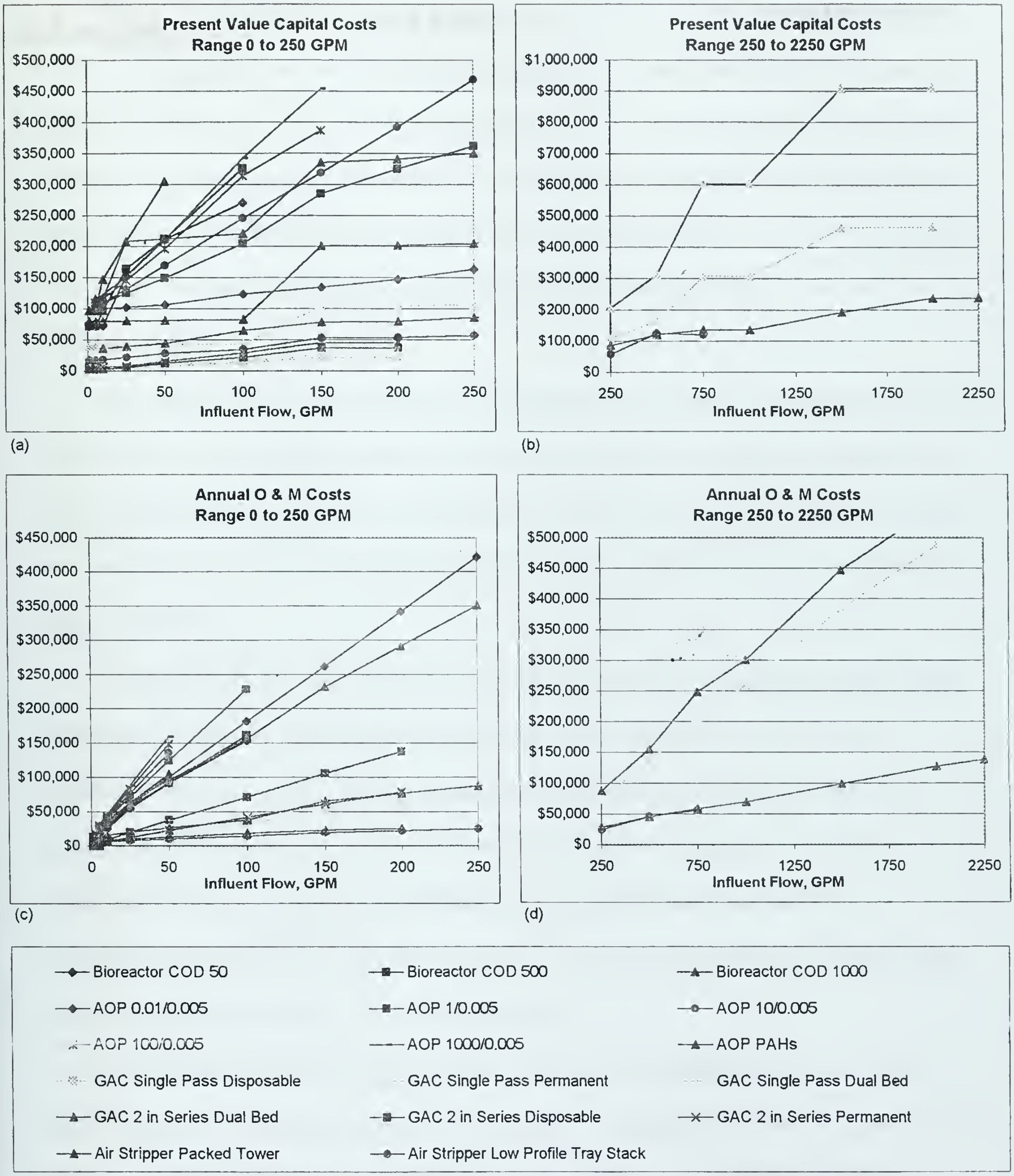

Figure (4) Cost versus influent flow for various SVOC and fuel treatment technologies.
(a) Comparison of capital costs for a range of flow between 0 and 250 GPM. (b) Comparison of capital costs for influent flow ranging from 250 to 2250 GPM. (c) Comparison of annual O & M costs for influent flow ranging from 0 to 250 GPM. (d) Comparision of annual O & M costs for technologies with influent flow ranging from 250 to 2250 gpm.

For all applicable contaminant classes, carbon adsorption and air stripping are the least cost technologies. Because carbon adsorption has the lowest capital cost for flow rates less than 250 gpm, (see Figures 3a, 4a, and 5a) it is typically the least cost technology for short treatment durations . As treatment durations increase, the technology selection will switch to air stripping, which has lower 12 month O & M costs for most flow rates (see Figures 3c, 3 d, 4c, 4d, 5c, and 5d). At low flow rates (less than 10 gpm), carbon adsorption will typically be the least cost technology choice.

For metals, the least cost technology is coagulation/flocculation. Both capital and O & M costs are less for coagulation/flocculation than metal precipitation. Appendix E compares the cost of treating metal contaminated groundwater at various flow rates. For metals, O & M costs are represented by a second order equation (see Table 5), but at higher flow rates, the O & M costs appear linear.

Bioreactors, AOPs, and precipitation are effective treatment technologies but have high capital and O & M cost that render them cost prohibitive for the purposes of this project. Situations exist where a site condition could make carbon adsorption or air stripping more expensive than bioreactors and AOPs. One such condition is the presence of high TOC concentrations. By performing several trials of varying influent flow rates and TOC concentrations, the effect on cost could be observed. TOC must be greater than 55 ppm before carbon adsorption is no longer the least cost technology.

The objective cost function developed for this project represents one segment of the overall strategy for treating contaminated groundwater. It is suitable for future incorporation into simulation and optimization models that aid environmental managers in decision making.

Appendices

Appendix A. Typical Contaminants in Each Contaminant Class

Appendices

Appendix A. Typical Contaminants in Each Contaminant Class

Typical halogenated VOCs

1,1,1,2-Tetrachloroethane	Bromoform	Glycerol trichlorohydrin
1,1,1-Trichloroethane	Bromomethane	Hexachlorobutadiene
1,1,2,2-Tetrachloroethane	Carbon tetrachloride	Hexachlorocyclopentadiene
1,1,2-Trichloroethane	Chlorodibromomethane	Hexachloroethane
1,1-Dichloroethane	Chloroethane	Methylene chloride
1,1-Dichloroethylene	Chloroform	Neoprene
1,2,2-Trifluoroethane (Freon 113)	Chloromethane	Pentachloroethane
1,2-Dichloroethane	Chloropropane	Perchloroethylene
1,2-Dichloropropane	Cis-1,2-dichloroethylene	Propylene dichloride
1,2-Trans-dichloroethylene	Cis-1,3-dichloropropene	Trichlorotrifluoroethane
1,3-cis-dichloro-1-propene	Dibromochloropropane	Monochlorobenzene
1,3-trans-dichloropropene	Dibromomethane	Tetrachloroethylene (Perchloroethylene) (PCE)
1-chloro-2-propene	Dichlorobromomethane	Trichloroethylene (TCE)
2-butylene dichloride	Dichloromethane	Vinyl chloride
Acetylene tetrachloride	Ethylene dibromide	Vinyl trichloride
Bromodichloromethane	Fluorotrichloromethane (Freon 11)	Vinylidene chloride

Nonhalogenated VOCs, excluding fuels and gas phase contaminants

1-butanol	Cyclohexanone	Methyl isobutyl ketone
4-Methyl-2-pentanone	Ethanol	n-Butyl alcohol
Acetone	Ethyl acetate	Styrene
Acrolein	Ethyl ether	Tetrahydrofuran
Acrylonitrile	Isobutanol	Vinyl acetate
Aminobenzene	Methanol	
Carbon disulfide	Methyl ethyl ketone (MEK)	

Typical halogenated SVOCs, excluding fuels and explosives

1,2,4-Trichlorobenzene	4-Chloroaniline	Hexachlorobenzene
1,2-Bis(2-chloroethoxy) ethane	4-Chlorophenyl phenylether	Hexachlorobutadiene
1,2-Dichlorobenzene	Bis(2-chloroethoxy) ether	Hexachlorocyclopentadiene
1,3-Dichlorobenzene	Bis(2-chloroethoxy) methane	o-dichlorobenzene
1,4-Dichlorobenzene	Bis(2-chloroethoxy) phthalate	p-Chloro-m-cresol
2,4,5-Trichlorophenol	Bis(2-chloroethyl) ether	p-dichlorobenzene
2,4,6-Trichlorophenol	Bis(2-chloroisopropyl) ether	Pentachlorobenzene
2,4-Dichlorophenol	Chlordane	Pentachlorophenol (PCP)
2-Chloronaphthalene	Chlorobenzene	Polychlorinated biphenyls (PCBs)
2-Chlorophenol	Chlorobenzilate	Quintozene
3,3-Dichlorobenzidine	Chlorphenothane	Tetrachlorophenol
4-Bromophenyl phenyl ether	Hexachlorobenzene	Unsym-trichlorobenzene

Typical nonhalogenated SVOCs, excluding fuels and explosives

1,2-benzacenaphthene	Benzidine	Ethyl parathion
1,2-Diphenylhydrazine	Benzo(a)anthracene	Fluorene
1-aminonaphathalene	Benzo(a)pyrene	Indeno(1,2,3-cd)pyrene
2,3-phenylenepyrene	Benzo(b)fluoranthene	Isophorone
2,4,-Dinitrophenol	Benzo(k)fluoranthene	Malathion
2-aminonaphthalene	Benzoic Acid	Methylparathion
2-Methylnaphthalene	Benzyl alcohol	Naphthalene
2-Nitroaniline	Bis(2-ethylhexyl)phthalate	n-Nitrosodimethylamine
2-Nitrophenol	Butyl benzyl phthalate	n-Nitrosodi-n-propylamine
3-Nitroaniline	Chrysene	n-Nitrosodiphenylamine
4,6-Dinitro-2-methylphenol	Dibenzofuran	Parathion
4-Nitroaniline	Diethyl phthalate	Phenanthrene
4-Nitrophenol	Dimethyl phthalate	Phenyl naphthalene
Acenaphthene	Di-n-butyl phthalate	Pyrene
Acenaphthylene	Di-n-octyl phthalate	Tetraphene
Allyldioxybenzene methylene ether	Diphenylenemethane	
Anthracene	Ethion	

Typical Fuel Contaminants

1,2,3,4-Tetramethylbenzene	2-Methylheptane	Benzo(k)fluoranthene	n-Decane
1,2,4,5-Tetramethylbenzene	2-Methylnaphthalene	Chrysene	n-Dodecane
1,2,4-Trimethyl-5-ethylbenzene	2-Methylpentane	Cis-2-butene	n-Heptane
1,2,4-Trimethylbenzene	2-Methylphenol	Creosols	n-Hexane
1,3,5-Trimethylbenzene	3,3,5-Trimethylheptane	Cyclohexane	n-Hexylbenzene
1-Pentene	3,3-Dimethyl-1-butene	Cyclopentane	n-Nonane
2,2,4-Trimethylheptane	3-Ethylpentane	Dibenzo(a,h)anthracene	n-Octane
2,2,4-Trimethylpentane	3-Methyl-1,2-butadiene	Dimethylethylbenzene	n-Pentane
2,2-Dimethylheptane	3-Methyl-1-butene	Ethylbenzene	n-Propylbenzene
2,2-Dimethylhexane	3-Methyl-1-pentene	Fluoranthene	n-Undecane
2,2-Dimethylpentane	3-Methylheptane	Fluorene	o-Xylene
2,3,4-Trimethylheptane	3-Methylhexane	Ideno(1,2,3-c,d)pyrene	Phenanthrene
2,3,4-Trimethylhexane	3-Methylpentane	Isobutane	Phenol
2,3,4-Trimethylpentane	4-Methylphenol	Isopentane	Propane
2,3-Dimethylbutane	Acenaphthene	Methylcyclohexane	p-Xylene
2,3-Dimethylpentane	Anthracene	Methylcyclopentane	Pyrene
2,4,4-Trimethylhexane	Benz(a)anthracene	Methylnaphthalene	Pyridine
2,4-Dimethylphenol	Benzene	Methylpropylbenzene	Toluene
2-Methyl-1,3-butadiene	Benzo(a)pyrene	m-Xylene	Trans-2-butene
2-Methyl-2-butene	Benzo(b)fluoranthene	Naphthalene	Trans-2-pentene
2-Methyl-butene	Benzo(g,h,i)perylene	n-Butane	Vinylbenzene

Typical ordnance contaminants

TNT (2,4,6-Trinitrotoluene)	Picrates
RDX (Cyclo-1,3,5-trimethylene-2,4,6-trinitramine)	TNB (Trinitrobenzenes)
Tetryl (N-Methyl-N,2,4,6-tetranitrobenzeneamine)	DNB (Dintrobenzenes)
2,4-DNT (2,4-Dinitrotoluene)	Nitroglycerine
2,6-DNT (2,6-Dinitrotoluene)	Nitrocellulose
HMX (1,3,5,7-Tetranitro-1,3,5,7-tetraazocyclooctane	AP (Ammonium perchlorate)
Nitroaromatics	Nitroglycerine

Typical Metal Contaminants

Alumina	Cobalt	Selenium
Aluminum	Copper	Silver
Antimony	Iron	Sodium
Arsenic*	Lead	Thallium
Barium	Magnesium	Tin
Beryllium	Manganese	Titanium
Bismuth	Mercury	Vanadium
Boron	Metallic cyanides	Zinc
Cadmium	Molybdenum	Zirconium
Calcium	Nickel	
Chromium	Potassium	

* Although arsenic is not a true metal, it is included here because it is classified as one of the eight RCRA metals

Appendix B. Summary of Technologies for VOCs

Capital VOC	Bioreactor COD (ppm) 50	500	1000	Advanced Oxidation Processes Trichloroethane - Influent Conc./Effluent Conc. (mg/L) 0.01/0.005	1/0.005	10/0.005	100/0.005	1000/0.005	1,2 DCA cis 1,2 DCE trans 1,2 DCE	GAC Single Pass Dual Bed	Disposable	Perm
1	$71,979	$71,979	$96,896	N/A	N/A	N/A	N/A	N/A	N/A	$40,361	$1,811	$3,928
5	$71,979	$71,979	$96,896	$100,389	$115,934	$115,934	$122,715	$129,645	$115,672	$40,361	$1,811	$3,928
10	$72,457	$97,375	$146,831	$100,389	$129,645	$136,296	$149,982	$163,493	$115,672	$40,361	$2,011	$3,928
25	$152,640	$164,123	$207,571	$111,412	$179,003	$206,287	$233,606	$267,571	$208,141	$41,325	$4,033	$4,892
50	$211,593	$211,698	$304,089	$122,127	$271,648	$305,864	$373,832	$441,238	$212,218	$42,367	$7,924	$9,464
100	$271,007	$325,230	N/A	$150,593	$416,026	N/A	N/A	N/A	$220,323	$43,777	$13,180	$16,818
150	N/A	N/A	N/A	$175,707	N/A	N/A	N/A	N/A	$334,978	$103,882	$21,770	$26,024
200	N/A	N/A	N/A	$201,614	N/A	N/A	N/A	N/A	$340,674	$104,274	$22,162	$26,416
250	N/A	N/A	N/A	$224,380	N/A	N/A	N/A	N/A	$349,791	$107,587	N/A	N/A
500	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	$162,839	N/A	N/A
750	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	$306,129	N/A	N/A
1000	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	$307,046	N/A	N/A
1500	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	$462,240	N/A	N/A
2000	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	$466,185	N/A	N/A
2250	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

O & M VOC GPM	Bioreactor COD (ppm) 50	500	1000	Advanced Oxidation Processes Trichloroethane - Influent Conc./Effluent Conc. (mg/L) 0.01/0.005	1/0.005	10/0.005	100/0.005	1000/0.005	Carbon Tetrachloride 1,1,2,2,PCA 1,2 DCA cis 1,2 DCE trans 1,2 DCE	GAC Single Pass Dual Bed	Disposable	Perm
1	$120,175	$120,175	$148,212	N/A	N/A	N/A	N/A	N/A	N/A	$64,773	$27,756	$25,594
5	$212,467	$212,467	$240,504	$284,630	$382,243	$421,175	$469,995	$516,725	$273,831	$88,122	$76,514	$56,198
10	$309,449	$337,486	$393,134	$426,387	$617,292	$704,897	$800,419	$895,742	$375,296	$110,559	$130,946	$87,705
25	$669,425	$682,347	$731,234	$833,863	$1,308,267	$1,538,142	$1,768,056	$2,014,483	$755,798	$170,769	$287,641	$175,123
50	$1,158,313	$1,158,432	$1,262,390	$1,492,938	$2,465,786	$2,906,023	$3,384,240	$3,861,823	$1,220,500	$264,722	$543,615	$318,390
100	$2,026,311	$2,087,322	N/A	$2,792,539	$4,702,675	N/A	N/A	N/A	$2,125,638	$436,312	$1,037,182	$587,361
150	N/A	N/A	N/A	$4,082,126	N/A	N/A	N/A	N/A	$3,144,426	$668,191	$1,528,747	$852,661
200	N/A	N/A	N/A	$5,363,933	N/A	N/A	N/A	N/A	$4,031,941	$834,202	$2,012,406	$1,109,364
250	N/A	N/A	N/A	$6,643,271	N/A	N/A	N/A	N/A	$4,924,369	$998,248	N/A	N/A
500	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	$1,849,776	N/A	N/A
750	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	$2,794,650	N/A	N/A
1000	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	$3,570,867	N/A	N/A
1500	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	$5,291,275	N/A	N/A
2000	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	$6,835,382	N/A	N/A
2250	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

Shaded cells indicate lowest cost for a particular flow rate

Total Cost (Capital + O & M for 15 years)

VOC	Bioreactor COD (ppm) 50	500	1000	Advanced Oxidation Processes Trichloroethane - Influent Conc./Effluent Conc. (mg/L) 0.01/0.005	1/0.005	10/0.005	100/0.005	1000/0.005	1,1,2,2,PCA 1,2 DCA cis 1,2 DCE trans 1,2 DCE	GAC Single Pass Dual Bed	Disposable	Perm
1	$192,154	$192,154	$245,108	N/A	N/A	N/A	N/A	N/A	N/A	$105,134	$29,567	$29,522
5	$284,446	$284,446	$337,400	$385,019	$498,177	$537,109	$592,710	$646,370	$389,503	$128,483	$78,325	$60,126
10	$381,906	$434,861	$539,965	$526,776	$746,937	$841,193	$950,401	$1,059,235	$490,968	$150,920	$132,957	$91,633
25	$822,065	$846,470	$938,805	$945,275	$1,487,270	$1,744,429	$2,001,662	$2,282,054	$963,939	$212,094	$291,674	$180,015
50	$1,369,906	$1,370,130	$1,566,479	$1,615,065	$2,737,434	$2,771,650	$3,758,072	$4,303,061	$1,432,718	$307,089	$551,539	$327,854
100	$2,297,318	$2,412,552	N/A	$2,943,132	$5,118,701	N/A	N/A	N/A	$2,345,961	$480,089	$1,050,362	$604,179
150	N/A	N/A	N/A	$4,257,833	N/A	N/A	N/A	N/A	$3,479,404	$772,073	$1,550,517	$878,685
200	N/A	N/A	N/A	$5,565,547	N/A	N/A	N/A	N/A	$4,372,615	$938,476	$2,034,568	$1,135,780
250	N/A	N/A	N/A	$6,867,651	N/A	N/A	N/A	N/A	$5,274,160	$1,105,835	N/A	N/A
500	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	$2,012,615	N/A	N/A
750	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	$3,100,779	N/A	N/A
1000	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	$3,877,913	N/A	N/A
1500	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	$5,753,515	N/A	N/A
2000	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	$7,301,567	N/A	N/A
2250	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

Typical 12 month O & M Costs

VOC GPM	Bioreactor COD (ppm) 50	500	1000	Advanced Oxidation Processes Trichloroethane - Influent Conc./Effluent Conc. (mg/L) 0.01/0.005	1/0.005	10/0.005	100/0.005	1000/0.005	Carbon Tetrachloride 1,1,2,2,PCA 1,2 DCA cis 1,2 DCE trans 1,2 DCE	GAC Single Pass Dual Bed	Disposable	Perm
1	$8,012	$8,012	$9,881	N/A	N/A	N/A	N/A	N/A	N/A	$4,318	$1,850	$1,706
5	$14,164	$14,164	$16,034	$18,975	$25,483	$28,078	$31,333	$34,448	$18,255	$5,875	$5,101	$3,747
10	$20,630	$22,499	$26,209	$28,426	$41,153	$46,993	$53,361	$59,716	$25,020	$7,371	$8,730	$5,847
25	$44,628	$45,490	$48,749	$55,591	$87,218	$102,543	$117,870	$134,299	$50,387	$11,385	$19,176	$11,675
50	$77,221	$77,229	$84,159	$99,529	$164,386	$193,735	$225,616	$257,455	$81,367	$17,648	$36,241	$21,226
100	$135,087	$139,155	N/A	$186,169	$313,512	N/A	N/A	N/A	$141,709	$29,087	$69,145	$39,157
150	N/A	N/A	N/A	$272,142	N/A	N/A	N/A	N/A	$209,628	$44,546	$101,916	$56,844
200	N/A	N/A	N/A	$357,596	N/A	N/A	N/A	N/A	$268,796	$55,613	$134,160	$73,958
250	N/A	N/A	N/A	$442,885	N/A	N/A	N/A	N/A	$328,291	$66,550	N/A	N/A
500	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	$123,318	N/A	N/A
750	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	$186,310	N/A	N/A
1000	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	$238,058	N/A	N/A
1500	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	$352,752	N/A	N/A
2000	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	$455,692	N/A	N/A
2250	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

Shaded cells indicate lowest cost for a particular flow rate

Capital VOC	GAC 2 in Series Dual Bed	Disposable Perm		Air Stripper Volatility Very High Packed Tower	Low Profile Tray Stack	Air Stripper Volatility Very High Packed Tower	Low Profile Tray Stack	Media Filtration
1	$79,447	$2,346	$6,581	N/A	$14,010	N/A	$16,076	$14,310
5	$79,447	$2,346	$6,581	N/A	$14,010	N/A	$16,076	$14,310
10	$79,447	$2,746	$6,581	$28,967	$15,250	$32,829	$17,317	$14,310
25	$80,411	$5,828	$7,545	$31,556	$17,101	$31,556	$19,968	$14,471
50	$81,453	$12,566	$15,646	$35,610	$22,951	$41,241	$25,818	$23,606
100	$82,862	$21,669	$28,945	$49,177	$28,731	$58,654	$31,198	$33,895
150	$201,385	$37,162	$45,670	$59,140	$41,337	$70,458	$46,870	$44,897
200	$201,777	$37,554	$46,062	$60,580	$41,782	$71,897	$47,315	$50,086
250	$205,091	N/A	N/A	$66,643	**$44,928**	$77,961	**$50,462**	$50,196
500	$311,368	N/A	N/A	**$91,748**	$93,999	**$109,309**	$110,999	N/A
750	$603,188	N/A	N/A	$96,301	**$88,591**	$120,180	**$105,591**	N/A
1000	$604,105	N/A	N/A	**$96,445**	N/A	**$120,324**	N/A	N/A
1500	$907,829	N/A	N/A	**$135,113**	N/A	**$166,951**	N/A	N/A
2000	$911,774	N/A	N/A	**$167,168**	N/A	**$207,076**	N/A	N/A
2250	N/A	N/A	N/A	**$168,228**	N/A	**$208,136**	N/A	N/A

O & M VOC GPM	GAC 2 in Series Dual Bed	Disposable Perm		Air Stripper Volatility Very High Packed Tower	Low Profile Tray Stack	Air Stripper Volatility High Packed Tower	Low Profile Tray Stack	Media Filtration
1	$108,752	$28,358	$28,579	N/A	$42,147	N/A	$44,473	$32,560
5	$132,101	$77,116	$59,183	N/A	**$55,184**	N/A	$57,509	$44,063
10	$154,538	$131,773	$90,690	$80,649	**$65,215**	$84,995	**$67,540**	$52,266
25	$214,749	$289,660	$178,108	$102,238	**$85,973**	$107,570	**$89,199**	$68,111
50	$308,701	$548,839	$325,347	$134,124	**$119,881**	$140,461	**$123,106**	$98,733
100	$480,291	$1,046,734	$601,007	$191,174	**$168,167**	$201,836	**$170,943**	$135,693
150	$777,902	$1,546,066	$874,767	$240,219	**$220,188**	$252,954	**$226,414**	$167,444
200	$943,913	$2,029,725	$1,131,469	$278,591	**$257,440**	$291,326	**$263,666**	$193,974
250	$1,107,958	N/A	N/A	$320,870	**$296,437**	$333,605	**$302,663**	$209,536
500	$2,016,901	N/A	N/A	$521,188	**$523,720**	$540,948	**$542,849**	N/A
750	$3,128,901	N/A	N/A	$697,110	**$671,884**	$723,978	**$707,563**	N/A
1000	$3,905,118	N/A	N/A	**$862,246**	N/A	$889,115	N/A	N/A
1500	$5,792,652	N/A	N/A	**$1,232,030**	N/A	$1,267,854	N/A	N/A
2000	$7,336,759	N/A	N/A	**$1,592,248**	N/A	$1,637,153	N/A	N/A
2250	N/A	N/A	N/A	**$1,754,740**	N/A	$1,799,645	N/A	N/A

Shaded cells indicate lowest cost for a particular flow rate

Total Cost

VOC	GAC 2 in Series Dual Bed	Disposable Perm		Air Stripper Volatility Very High Packed Tower	Low Profile Tray Stack	Air Stripper Volatility Very High Packed Tower	Low Profile Tray Stack	Media Filtration
1	$188,199	$30,704	$35,160	N/A	$56,157	N/A	$60,549	$46,870
5	$211,548	$79,462	$65,764	N/A	$69,194	N/A	$73,585	$58,373
10	$233,985	$134,519	$97,271	$109,616	**$80,465**	$117,824	**$84,857**	$66,576
25	$295,160	$295,488	$185,653	$133,794	**$103,074**	$139,126	**$109,167**	$82,582
50	$390,154	$561,405	$340,993	$169,734	**$142,832**	$181,702	**$148,924**	$122,339
100	$563,153	$1,068,403	$629,952	$240,351	**$196,898**	$260,490	**$202,141**	$169,588
150	$979,287	$1,583,228	$920,437	$299,359	**$261,525**	$323,412	**$273,284**	$212,341
200	$1,145,690	$2,067,279	$1,177,531	$339,171	**$299,222**	$363,223	**$310,981**	$244,060
250	$1,313,049	N/A	N/A	$387,513	**$341,365**	$411,566	**$353,125**	$259,732
500	$2,328,269	N/A	N/A	$612,936	**$617,719**	$650,257	**$653,848**	N/A
750	$3,732,089	N/A	N/A	$793,411	**$760,475**	$844,158	**$813,154**	N/A
1000	$4,509,223	N/A	N/A	**$958,691**	N/A	$1,009,439	N/A	N/A
1500	$6,700,481	N/A	N/A	**$1,367,143**	N/A	$1,434,805	N/A	N/A
2000	$8,248,533	N/A	N/A	**$1,759,416**	N/A	$1,844,229	N/A	N/A
2250	N/A	N/A	N/A	**$1,922,968**	N/A	$2,007,781	N/A	N/A

Typical 12

VOC GPM	GAC 2 in Series Dual Bed	Disposable Perm		Air Stripper Volatility Very High Packed Tower	Low Profile Tray Stack	Air Stripper Volatility High Packed Tower	Low Profile Tray Stack	Media Filtration
1	$7,250	$1,891	$1,905	N/A	$2,810	N/A	$2,965	$2,171
5	$8,807	$5,141	$3,946	N/A	**$3,679**	N/A	**$3,834**	$2,938
10	$10,303	$8,785	$6,046	$5,377	**$4,348**	$5,666	**$4,503**	$3,484
25	$14,317	$19,311	$11,874	$6,816	**$5,732**	$7,171	**$5,947**	$4,541
50	$20,580	$36,589	$21,690	$8,942	**$7,992**	$9,364	**$8,207**	$6,582
100	$32,019	$69,782	$40,067	$12,745	**$11,211**	$13,456	**$11,396**	$9,046
150	$51,860	$103,071	$58,318	$16,015	**$14,679**	$16,864	**$15,094**	$11,163
200	$62,928	$135,315	$75,431	$18,573	**$17,163**	$19,422	**$17,578**	$12,932
250	$73,864	N/A	N/A	$21,391	**$19,762**	$22,240	**$20,178**	$13,969
500	$134,460	N/A	N/A	$34,746	**$34,915**	$36,063	**$36,190**	N/A
750	$208,593	N/A	N/A	$46,474	**$44,792**	$48,265	**$47,171**	N/A
1000	$260,341	N/A	N/A	**$57,483**	N/A	$59,274	N/A	N/A
1500	$386,177	N/A	N/A	**$82,135**	N/A	$84,524	N/A	N/A
2000	$489,117	N/A	N/A	**$106,150**	N/A	$109,144	N/A	N/A
2250	N/A	N/A	N/A	**$116,983**	N/A	$119,976	N/A	N/A

Shaded cells indicate lowest cost for a particular flow rate

Appendix C. Summary of Technologies for SVOCs

Capital	Bioreactor			Advanced Oxidation Processes					PAHs	GAC			GAC		
	COD (ppm)			Phenol - Influent Conc./Effluent Conc. (mg/L)						Single Pass			2 in Series		
SVOC	50	500	1000	0.01/0.005	1/0.005	10/0.005	100/0.005	1000/0.005		Dual Bed	Disposable	Perm	Dual Bed	Disposable	Perm
1	$71,979	$71,979	$96,896	N/A	N/A	N/A	N/A	N/A	N/A	$40,361	$1,811	$3,928	$79,447	$2,346	$6,581
5	$71,979	$71,979	$96,896	$100,389	$100,389	$100,389	$109,296	$109,296	$115,672	$40,361	$1,811	$3,928	$79,447	$2,346	$6,581
10	$72,457	$97,375	$146,831	$100,389	$109,296	$109,296	$115,934	$122,715	$115,672	$40,361	$2,011	$3,928	$79,447	$2,746	$6,581
25	$152,640	$164,123	$207,571	$102,504	$124,831	$131,761	$145,173	$152,098	$208,141	$41,325	$4,033	$4,892	$80,411	$5,828	$7,545
50	$211,593	$211,698	$304,089	$106,582	$149,251	$169,686	$196,729	$210,364	$212,218	$42,367	$7,924	$9,464	$81,453	$12,566	$15,646
100	$271,007	$325,230	N/A	$123,593	$204,833	$245,787	$313,968	$342,223	$220,323	$43,777	$13,180	$16,818	$82,862	$21,669	$28,945
150	N/A	N/A	N/A	$134,964	$284,485	$318,701	$386,670	$454,076	$334,978	$103,882	$21,770	$26,024	$201,385	$37,162	$45,670
200	N/A	N/A	N/A	$147,442	$324,397	$392,365	N/A	N/A	$340,674	$104,274	$22,162	$26,416	$201,777	$37,554	$46,062
250	N/A	N/A	N/A	$163,489	$361,770	$468,889	N/A	N/A	$349,791	$107,587	N/A	N/A	$205,091	N/A	N/A
500	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	$162,839	N/A	N/A	$311,368	N/A	N/A
750	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	$306,129	N/A	N/A	$603,188	N/A	N/A
1000	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	$307,046	N/A	N/A	$604,105	N/A	N/A
1500	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	$462,240	N/A	N/A	$907,829	N/A	N/A
2000	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	$466,185	N/A	N/A	$911,774	N/A	N/A
2250	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

O&M	Bioreactor			Advanced Oxidation Processes					PAHs	GAC			GAC		
	COD (ppm)			Phenol - Influent Conc./Effluent Conc. (mg/L)						Single Pass			2 in Series		
SVOC	50	500	1000	0.01/0.005	1/0.005	10/0.005	100/0.005	1000/0.005		Dual Bed	Disposable	Perm	Dual Bed	Disposable	Perm
1	$120,175	$120,175	$148,212	N/A	N/A	N/A	N/A	N/A	N/A	$64,773	$27,756	$25,594	$108,752	$28,358	$28,579
5	$212,467	$212,467	$240,504	$277,724	$302,925	$316,655	$340,408	$354,138	$273,831	$88,122	$76,514	$56,198	$132,101	$77,116	$59,183
10	$309,449	$337,486	$393,134	$410,316	$473,000	$500,461	$533,130	$568,221	$375,296	$110,559	$130,946	$87,705	$154,538	$131,773	$90,690
25	$669,425	$682,347	$731,234	$784,791	$942,696	$1,016,886	$1,098,369	$1,172,552	$755,798	$170,769	$287,641	$175,123	$214,749	$289,660	$178,108
50	$1,158,313	$1,158,432	$1,262,390	$1,395,090	$1,708,668	$1,864,444	$2,027,657	$2,175,783	$1,220,500	$264,722	$543,615	$318,390	$308,701	$548,839	$325,347
100	$2,026,311	$2,087,322	N/A	$2,601,444	$3,223,988	$3,535,636	$3,888,461	$4,188,079	$2,125,638	$436,312	$1,037,182	$587,361	$480,291	$1,046,734	$601,007
150	N/A	N/A	N/A	$3,797,467	$4,770,314	$5,210,552	$5,688,768	$6,166,352	$3,144,426	$668,191	$1,528,747	$852,661	$777,902	$1,546,066	$874,767
200	N/A	N/A	N/A	$4,983,805	$6,257,229	$6,869,358	N/A	N/A	$4,031,941	$834,202	$2,012,406	$1,109,364	$943,913	$2,029,725	$1,131,469
250	N/A	N/A	N/A	$6,175,225	$7,742,352	$8,532,446	N/A	N/A	$4,924,369	$998,248	N/A	N/A	$1,107,958	N/A	N/A
500	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	$1,849,776	N/A	N/A	$2,016,901	N/A	N/A
750	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	$2,794,650	N/A	N/A	$3,128,901	N/A	N/A
1000	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	$3,570,867	N/A	N/A	$3,905,118	N/A	N/A
1500	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	$5,291,275	N/A	N/A	$5,792,652	N/A	N/A
2000	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	$6,835,382	N/A	N/A	$7,336,759	N/A	N/A
2250	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

Shaded cells indicate lowest cost for a particular flow rate

Total Present Value Cost (Capital + O & M for 15 years)

SVOC	Bioreactor COD (ppm) 50	500	1000	Advanced Oxidation Processes Phenol - Influent Conc./Effluent Conc. (mg/L) 0.01/0.005	1/0.005	10/0.005	100/0.005	1000/0.005	PAHs	GAC Single Pass Dual Bed	Disposable	Perm	GAC 2 in Series Dual Bed	Disposable	Perm
1	$192,154	$192,154	$245,108	N/A	N/A	N/A	N/A	N/A	N/A	$105,134	$29,567	$29,522	$188,199	$30,704	$35,160
5	$284,446	$284,446	$337,400	$378,113	$403,314	$417,044	$449,704	$463,434	$389,503	$128,483	$78,325	$60,126	$211,548	$79,462	$65,764
10	$381,906	$434,861	$539,965	$510,705	$582,296	$609,757	$649,064	$690,936	$490,968	$150,920	$132,957	$91,633	$233,985	$134,519	$97,271
25	$822,065	$846,470	$938,805	$887,295	$1,067,527	$1,148,647	$1,243,542	$1,324,650	$963,939	$212,094	$291,674	$180,015	$295,160	$295,488	$185,653
50	$1,369,906	$1,370,130	$1,566,479	$1,501,672	$1,857,919	$2,034,130	$2,224,386	$2,386,147	$1,432,718	$307,089	$551,539	$327,854	$390,154	$561,405	$340,993
100	$2,297,318	$2,412,552	N/A	$2,725,037	$3,428,821	$3,781,423	$4,202,429	$4,530,302	$2,345,961	$480,089	$1,050,362	$604,179	$563,153	$1,068,403	$629,952
150	N/A	N/A	N/A	$3,932,431	$5,054,799	$5,529,253	$6,075,438	$6,620,428	$3,479,404	$772,073	$1,550,517	$878,685	$979,287	$1,583,228	$920,437
200	N/A	N/A	N/A	$5,131,247	$6,581,626	$7,261,723	N/A	N/A	$4,372,615	$938,476	$2,034,568	$1,135,780	$1,145,690	$2,067,279	$1,177,531
250	N/A	N/A	N/A	$6,338,714	$8,104,122	$9,001,335	N/A	N/A	$5,274,160	$1,105,835	N/A	N/A	$1,313,049	N/A	N/A
500	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	$2,012,615	N/A	N/A	$2,328,269	N/A	N/A
750	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	$3,100,779	N/A	N/A	$3,732,089	N/A	N/A
1000	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	$3,877,913	N/A	N/A	$4,509,223	N/A	N/A
1500	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	$5,753,515	N/A	N/A	$6,700,481	N/A	N/A
2000	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	$7,301,567	N/A	N/A	$8,248,533	N/A	N/A
2250	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

Typical 12 month O & M Cost

SVOC	Bioreactor COD (ppm) 50	500	1000	Advanced Oxidation Processes Phenol - Influent Conc./Effluent Conc. (mg/L) 0.01/0.005	1/0.005	10/0.005	100/0.005	1000/0.005	PAHs	GAC Single Pass Dual Bed	Disposable	Perm	GAC 2 in Series Dual Bed	Disposable	Perm
1	$12,810	$12,810	$16,341	N/A	N/A	N/A	N/A	N/A	N/A	$7,009	$1,971	$1,968	$12,547	$2,047	$2,344
5	$18,963	$18,963	$22,493	$25,208	$26,888	$27,803	$29,980	$30,896	$25,967	$8,566	$5,222	$4,008	$14,103	$5,297	$4,384
10	$25,460	$28,991	$35,998	$34,047	$38,820	$40,650	$43,271	$46,062	$32,731	$10,061	$8,864	$6,109	$15,599	$8,968	$6,485
25	$54,804	$56,431	$62,587	$59,153	$71,168	$76,576	$82,903	$88,310	$64,263	$14,140	$19,445	$12,001	$19,677	$19,699	$12,377
50	$91,327	$91,342	$104,432	$100,111	$123,861	$135,609	$148,292	$159,076	$95,515	$20,473	$36,769	$21,857	$26,010	$37,427	$22,733
100	$153,155	$160,837	N/A	$181,669	$228,588	$252,095	$280,162	$302,020	$156,397	$32,006	$70,024	$40,279	$37,544	$71,227	$41,997
150	N/A	N/A	N/A	$262,162	$336,987	$368,617	$405,029	$441,362	$231,960	$51,472	$103,368	$58,579	$65,286	$105,549	$61,362
200	N/A	N/A	N/A	$342,083	$438,775	$484,115	N/A	N/A	$291,508	$62,565	$135,638	$75,719	$76,379	$137,819	$78,502
250	N/A	N/A	N/A	$422,581	$540,275	$600,089	N/A	N/A	$351,611	$73,722	N/A	N/A	$87,537	N/A	N/A
500	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	$134,174	N/A	N/A	$155,218	N/A	N/A
750	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	$206,719	N/A	N/A	$248,806	N/A	N/A
1000	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	$258,528	N/A	N/A	$300,615	N/A	N/A
1500	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	$383,568	N/A	N/A	$446,699	N/A	N/A
2000	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	$486,771	N/A	N/A	$549,902	N/A	N/A
2250	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

Shaded cells indicate lowest cost for a particular flow rate

Capital SVOC	Air Stripper Volatility Moderate Packed Tower	Air Stripper Volatility Moderate Low Profile Tray Stack	Media Filtration
1	N/A	$17,143	$14,310
5	N/A	$17,143	$14,310
10	$35,833	$18,383	$14,310
25	$39,420	$21,701	$14,471
50	$44,533	$28,018	$23,606
100	$64,629	$34,398	$33,895
150	$78,189	$53,570	$44,897
200	$79,628	$54,015	$50,086
250	$85,692	$57,162	$50,196
500	$120,691	$124,665	N/A
750	$135,345	$119,258	N/A
1000	$136,489	N/A	N/A
1500	$190,872	N/A	N/A
2000	$236,788	N/A	N/A
2250	$237,847	N/A	N/A

O&M SVOC	Air Stripper Volatility Moderate Packed Tower	Air Stripper Volatility Moderate Low Profile Tray Stack	Media Filtration
1	N/A	$45,673	$32,560
5	N/A	$58,709	$44,063
10	$88,375	$68,741	$52,266
25	$111,087	$91,149	$68,111
50	$144,164	$125,582	$98,733
100	$208,560	$174,543	$135,693
150	$261,653	$233,953	$167,444
200	$300,025	$271,205	$193,974
250	$342,304	$310,202	$209,536
500	$553,755	$558,226	N/A
750	$741,042	$722,941	N/A
1000	$906,179	N/A	N/A
1500	$1,294,769	N/A	N/A
2000	$1,670,584	N/A	N/A
2250	$1,833,076	N/A	N/A

Shaded cells indicate lowest cost for a particular flow rate

Total Pres

SVOC	Air Stripper Volatility Moderate Packed Tower	Low Profile Tray Stack	Media Filtration
1	N/A	$62,816	$46,870
5	N/A	$75,852	$58,373
10	$124,208	$87,124	$66,576
25	$150,507	$112,850	$82,582
50	$188,697	$153,600	$122,339
100	$273,189	$208,941	$169,588
150	$339,842	$287,523	$212,341
200	$379,653	$325,220	$244,060
250	$427,996	$367,364	$259,732
500	$674,446	$682,891	N/A
750	$876,387	$842,199	N/A
1000	$1,041,668	N/A	N/A
1500	$1,485,641	N/A	N/A
2000	$1,907,372	N/A	N/A
2250	$2,070,923	N/A	N/A

Typical 12

SVOC	Air Stripper Volatility Moderate Packed Tower	Low Profile Tray Stack	Media Filtration
1	N/A	$4,188	$3,125
5	N/A	$5,057	$3,892
10	$8,281	$5,808	$4,438
25	$10,034	$7,523	$5,505
50	$12,580	$10,240	$8,156
100	$18,213	$13,929	$11,306
150	$22,656	$19,168	$14,156
200	$25,310	$21,681	$16,271
250	$28,533	$24,491	$17,315
500	$44,963	$45,526	N/A
750	$58,426	$56,147	N/A
1000	$69,445	N/A	N/A
1500	$99,043	N/A	N/A
2000	$127,158	N/A	N/A
2250	$138,082	N/A	N/A

Shaded cells indicate lowest cost for a particular flow rate

Appendix D. Summary of Technologies for Fuels

Capital Costs Fuels	Bioreactor COD (ppm) 50	500	1000	Advanced Oxidation Processes Benzene - Influent Conc./Effluent Conc. (mg/L) 0.01/0.005	1/0.005	10/0.005	100/0.005	1000/0.005	Ethyl benzene	GAC Single Pass Dual Bed	Disposable	Perm	GAC 2 in Series Dual Bed	Disposabl	Perm
1	$71,979	$71,979	$96,896	N/A	N/A	N/A	N/A	N/A	N/A	$40,361	**$1,811**	$3,928	$79,447	$2,346	$6,581
5	$71,979	$71,979	$96,896	$100,389	$100,389	$100,389	$109,296	$109,296	$115,672	$40,361	**$1,811**	$3,928	$79,447	$2,346	$6,581
10	$72,457	$97,375	$146,831	$100,389	$109,296	$109,296	$115,934	$122,715	$115,672	$40,361	**$2,011**	$3,928	$79,447	$2,746	$6,581
25	$152,640	$164,123	$207,571	$102,504	$124,831	$131,761	$145,173	$152,098	$208,141	$41,325	**$4,033**	$4,892	$80,411	$5,828	$7,545
50	$211,593	$211,698	$304,089	$106,582	$149,251	$169,686	$196,729	$210,364	$212,218	$42,367	**$7,924**	$9,464	$81,453	$12,566	$15,646
100	$271,007	$325,230	N/A	$123,593	$204,833	$245,787	$313,968	$342,223	$220,323	$43,777	**$13,180**	$16,818	$82,862	$21,669	$28,945
150	N/A	N/A	N/A	$134,964	$284,485	$318,701	$386,670	$454,076	$334,978	$103,882	**$21,770**	$26,024	$201,385	$37,162	$45,670
200	N/A	N/A	N/A	$147,442	$324,397	$392,365	N/A	N/A	$340,674	$104,274	**$22,162**	$26,416	$201,777	$37,554	$46,062
250	N/A	N/A	N/A	$163,489	$361,770	$468,889	N/A	N/A	$349,791	$107,587	N/A	N/A	$205,091	N/A	N/A
500	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	$162,839	N/A	N/A	$311,368	N/A	N/A
750	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	$306,129	N/A	N/A	$603,188	N/A	N/A
1000	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	$307,046	N/A	N/A	$604,105	N/A	N/A
1500	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	$462,240	N/A	N/A	$907,829	N/A	N/A
2000	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	$466,185	N/A	N/A	$911,774	N/A	N/A
2250	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

O&M Costs Fuels	Bioreactor COD (ppm) 50	500	1000	Advanced Oxidation Processes Benzene - Influent Conc./Effluent Conc. (mg/L) 0.01/0.005	1/0.005	10/0.005	100/0.005	1000/0.005	Ethyl benzene	GAC Single Pass Dual Bed	Disposable	Perm	GAC 2 in Series Dual Bed	Disposabl	Perm
1	$120,175	$120,175	$148,212	N/A	N/A	N/A	N/A	N/A	N/A	$64,773	$27,756	**$25,594**	$108,752	$28,358	$28,579
5	$212,467	$212,467	$240,504	$277,724	$302,925	$316,655	$340,408	$354,138	$273,831	$88,122	$76,514	**$56,198**	$132,101	$77,116	$59,183
10	$309,449	$337,486	$393,134	$410,316	$473,000	$500,461	$533,130	$568,221	$375,296	$110,559	$130,946	**$87,705**	$154,538	$131,773	$90,690
25	$669,425	$682,347	$731,234	$784,791	$942,696	$1,016,886	$1,098,369	$1,172,552	$755,798	$170,769	$287,641	$175,123	$214,749	$289,660	$178,108
50	$1,158,313	$1,158,432	$1,262,390	$1,395,090	$1,708,668	$1,864,444	$2,027,657	$2,175,783	$1,220,500	$264,722	$543,615	$318,390	$308,701	$548,839	$325,347
100	$2,026,311	$2,087,322	N/A	$2,601,444	$3,223,988	$3,535,636	$3,888,461	$4,188,079	$2,125,638	$436,312	$1,037,182	$587,361	$480,291	$1,046,734	$601,007
150	N/A	N/A	N/A	$3,797,467	$4,770,314	$5,210,552	$5,688,768	$6,166,352	$3,144,426	$668,191	$1,528,747	$852,661	$777,902	$1,546,066	$874,767
200	N/A	N/A	N/A	$4,983,805	$6,257,229	$6,869,358	N/A	N/A	$4,031,941	$834,202	$2,012,406	$1,109,364	$943,913	$2,029,725	$1,131,469
250	N/A	N/A	N/A	$6,175,225	$7,742,352	$8,532,446	N/A	N/A	$4,924,369	$998,248	N/A	N/A	$1,107,958	N/A	N/A
500	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	$1,849,776	N/A	N/A	$2,016,901	N/A	N/A
750	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	$2,794,650	N/A	N/A	$3,128,901	N/A	N/A
1000	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	$3,570,867	N/A	N/A	$3,905,118	N/A	N/A
1500	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	$5,291,275	N/A	N/A	$5,792,652	N/A	N/A
2000	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	$6,835,382	N/A	N/A	$7,336,759	N/A	N/A
2250	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

Shaded cells indicate lowest cost for a particular flow rate

Total Costs Fuels	Bioreactor COD (ppm) 50	500	1000	Advanced Oxidation Processes Benzene - Influent Conc./Effluent Conc. (mg/L) 0.01/0.005	1/0.005	10/0.005	100/0.005	1000/0.005	Ethyl benzene	GAC Single Pass Dual Bed	Disposable	Perm	GAC 2 in Series Dual Bed	Disposabl	Perm
1	$192,154	$192,154	$245,108	N/A	N/A	N/A	N/A	N/A	N/A	$105,134	$29,567	$29,522	$188,199	$30,704	$35,160
5	$284,446	$284,446	$337,400	$378,113	$403,314	$417,044	$449,704	$463,434	$389,503	$128,483	$78,325	$60,126	$211,548	$79,462	$65,764
10	$381,906	$434,861	$539,965	$510,705	$582,296	$609,757	$649,064	$690,936	$490,968	$150,920	$132,957	$91,633	$233,985	$134,519	$97,271
25	$822,065	$846,470	$938,805	$887,295	$1,067,527	$1,148,647	$1,243,542	$1,324,650	$963,939	$212,094	$291,674	$180,015	$295,160	$295,488	$185,653
50	$1,369,906	$1,370,130	$1,566,479	$1,501,672	$1,857,919	$2,034,130	$2,224,386	$2,386,147	$1,432,718	$307,089	$551,539	$327,854	$390,154	$561,405	$340,993
100	$2,297,318	$2,412,552	N/A	$2,725,037	$3,428,821	$3,781,423	$4,202,429	$4,530,302	$2,345,961	$480,089	$1,050,362	$604,179	$563,153	$1,068,403	$629,952
150	N/A	N/A	N/A	$3,932,431	$5,054,799	$5,529,253	$6,075,438	$6,620,428	$3,479,404	$772,073	$1,550,517	$878,685	$979,287	$1,583,228	$920,437
200	N/A	N/A	N/A	$5,131,247	$6,581,626	$7,261,723	N/A	N/A	$4,372,615	$938,476	$2,034,568	$1,135,780	$1,145,690	$2,067,279	$1,177,531
250	N/A	N/A	N/A	$6,338,714	$8,104,122	$9,001,335	N/A	N/A	$5,274,160	$1,105,835	N/A	N/A	$1,313,049	N/A	N/A
500	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	$2,012,615	N/A	N/A	$2,328,269	N/A	N/A
750	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	$3,100,779	N/A	N/A	$3,732,089	N/A	N/A
1000	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	$3,877,913	N/A	N/A	$4,509,223	N/A	N/A
1500	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	$5,753,515	N/A	N/A	$6,700,481	N/A	N/A
2000	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	$7,301,567	N/A	N/A	$8,248,533	N/A	N/A
2250	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

Typical 12 Month O & M Costs

Fuels	Bioreactor COD (ppm) 50	500	1000	Advanced Oxidation Processes Benzene - Influent Conc./Effluent Conc. (mg/L) 0.01/0.005	1/0.005	10/0.005	100/0.005	1000/0.005	Ethyl benzene	GAC Single Pass Dual Bed	Disposable	Perm	GAC 2 in Series Dual Bed	Disposabl	Perm
1	$8,012	$8,012	$9,881	N/A	N/A	N/A	N/A	N/A	N/A	$4,318	$1,850	$1,706	$7,250	$1,891	$1,905
5	$14,164	$14,164	$16,034	$18,515	$20,195	$21,110	$22,694	$23,609	$18,255	$5,875	$5,101	$3,747	$8,807	$5,141	$3,946
10	$20,630	$22,499	$26,209	$27,354	$31,533	$33,364	$35,542	$37,881	$25,020	$7,371	$8,730	$5,847	$10,303	$8,785	$6,046
25	$44,628	$45,490	$48,749	$52,319	$62,846	$67,792	$73,225	$78,170	$50,387	$11,385	$19,176	$11,675	$14,317	$19,311	$11,874
50	$77,221	$77,229	$84,159	$93,006	$113,911	$124,296	$135,177	$145,052	$81,367	$17,648	$36,241	$21,226	$20,580	$36,589	$21,690
100	$135,087	$139,155	N/A	$173,430	$214,933	$235,709	$259,231	$279,205	$141,709	$29,087	$69,145	$39,157	$32,019	$69,782	$40,067
150	N/A	N/A	N/A	$253,164	$318,021	$347,370	$379,251	$411,090	$209,628	$44,546	$101,916	$56,844	$51,860	$103,071	$58,318
200	N/A	N/A	N/A	$332,254	$417,149	$457,957	N/A	N/A	$268,796	$55,613	$134,160	$73,958	$62,928	$135,315	$75,431
250	N/A	N/A	N/A	$411,682	$516,157	$568,830	N/A	N/A	$328,291	$66,550	N/A	N/A	$73,864	N/A	N/A
500	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	$123,318	N/A	N/A	$134,460	N/A	N/A
750	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	$186,310	N/A	N/A	$208,593	N/A	N/A
1000	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	$238,058	N/A	N/A	$260,341	N/A	N/A
1500	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	$352,752	N/A	N/A	$386,177	N/A	N/A
2000	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	$455,692	N/A	N/A	$489,117	N/A	N/A
2250	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

Shaded cells indicate lowest cost for a particular flow rate

Capital Costs	Air Stripper Volatility Moderate		Media Filtration
Fuels	Packed Tower	Low Profile Tray Stack	
1	N/A	$17,143	$14,310
5	N/A	$17,143	$14,310
10	$35,833	$18,383	$14,310
25	$39,420	$21,701	$14,471
50	$44,533	$28,018	$23,606
100	$64,629	$34,398	$33,895
150	$78,189	$53,570	$44,897
200	$79,628	$54,015	$50,086
250	$85,692	$57,162	$50,196
500	$120,691	$124,665	N/A
750	$135,345	$119,258	N/A
1000	$135,489	N/A	N/A
1500	$190,872	N/A	N/A
2000	$236,788	N/A	N/A
2250	$237,847	N/A	N/A

O&M Costs	Air Stripper Volatility Moderate		Media Filtration
Fuels	Packed Tower	Low Profile Tray Stack	
1	N/A	$45,673	$32,560
5	N/A	$58,709	$44,063
10	$88,375	$68,741	$52,266
25	$111,087	$91,149	$68,111
50	$144,164	$125,582	$98,733
100	$208,560	$174,543	$135,693
150	$261,653	$233,953	$167,444
200	$300,025	$271,205	$193,974
250	$342,304	$310,202	$209,536
500	$553,755	$558,226	N/A
750	$741,042	$722,941	N/A
1000	$906,179	N/A	N/A
1500	$1,294,769	N/A	N/A
2000	$1,670,584	N/A	N/A
2250	$1,833,076	N/A	N/A

Shaded cells indicate lowest cost for a particular flow rate

Total Costs Fuels	Air Stripper Volatility Moderate Packed Tower	Low Profile Tray Stack	Media Filtration
1	N/A	$62,816	$46,870
5	N/A	$75,852	$58,373
10	$124,208	$87,124	$66,576
25	$150,507	$112,850	$82,582
50	$188,697	$153,600	$122,339
100	$273,189	$208,941	$169,588
150	$339,842	$287,523	$212,341
200	$379,653	$325,220	$244,060
250	$427,996	$367,364	$259,732
500	$674,446	$682,891	N/A
750	$876,387	$842,199	N/A
1000	$1,041,668	N/A	N/A
1500	$1,485,641	N/A	N/A
2000	$1,907,372	N/A	N/A
2250	$2,070,923	N/A	N/A

Typical Fuels	12 Month O & M Costs Air Stripper Volatility Moderate Packed Tower	Low Profile Tray Stack	Media Filtration
1	N/A	$3,045	$2,171
5	N/A	$3,914	$2,938
10	$5,892	$4,583	$3,484
25	$7,406	$6,077	$4,541
50	$9,611	$8,372	$6,582
100	$13,904	$11,636	$9,046
150	$17,444	$15,597	$11,163
200	$20,002	$18,080	$12,932
250	$22,820	$20,680	$13,969
500	$36,917	$37,215	N/A
750	$49,403	$48,196	N/A
1000	$60,412	N/A	N/A
1500	$86,318	N/A	N/A
2000	$111,372	N/A	N/A
2250	$122,205	N/A	N/A

Shaded cells indicate lowest cost for a particular flow rate

Appendix E. Summary of Technologies for Metals

Capital Cost Metals Influent flow, GPM	Coagulation/Flocculation	Media Filtration
1	$73,873	$14,310
5	$73,949	$14,310
10	$74,025	$14,310
25	$74,416	$14,471
50	$104,981	$23,606
75	$130,341	$27,185
100	$131,048	$33,895
150	$160,366	$44,897
175	$160,824	$44,897
200	$161,206	$50,086
250	$188,513	$50,196
300	$189,353	N/A
400	$230,779	N/A
500	$232,536	N/A
600	$294,906	N/A
700	$296,663	N/A
750	$297,580	N/A
800	$298,420	N/A
900	$382,380	N/A
1000	$384,137	N/A
1100	$385,894	N/A
1250	$463,397	N/A
1500	$467,752	N/A
1645	$471,983	N/A

O & M Costs Metals Influent flow, GPM	Coagulation/Flocculation	Media Filtration
1	$107,504	$32,560
5	$128,619	$44,063
10	$145,681	$52,266
25	$185,657	$68,111
50	$266,747	$98,733
75	$340,243	$116,514
100	$378,518	$135,693
150	$482,384	$167,444
175	$520,449	$176,225
200	$554,172	$193,974
250	$648,935	$209,536
300	$712,368	N/A
400	$884,234	N/A
500	$1,004,558	N/A
600	$1,194,916	N/A
700	$1,311,097	N/A
750	$1,368,816	N/A
800	$1,426,193	N/A
900	$1,632,745	N/A
1000	$1,749,673	N/A
1100	$1,862,391	N/A
1250	$2,114,117	N/A
1500	$2,394,405	N/A
1645	$2,556,140	N/A

Total Cost (Capital + 15 yr O & M) Metals Influent flow, GPM	Coagulation/Flocculation	Media Filtration
1	$181,377	$46,870
5	$202,568	$58,373
10	$219,706	$66,576
25	$260,073	$82,582
50	$371,728	$122,339
75	$470,584	$143,699
100	$509,566	$169,588
150	$642,750	$212,341
175	$681,273	$221,122
200	$715,378	$244,060
250	$837,448	$259,732
300	$901,721	
400	$1,115,013	
500	$1,237,094	
600	$1,489,822	
700	$1,607,760	
750	$1,666,396	
800	$1,724,613	
900	$2,015,125	
1000	$2,133,810	
1100	$2,248,285	
1250	$2,577,514	
1500	$2,862,157	
1645	$3,028,123	

Annual O&M Metals Influent flow, GPM	Coagulation/Flocculation	Media Filtration
1	$7,166.93	$2,170.67
5	$8,574.60	$2,937.53
10	$9,712.07	$3,484.40
25	$12,377.13	$4,540.73
50	$17,783.13	$6,582.20
75	$22,682.87	$7,767.60
100	$25,234.53	$9,046.20
150	$32,158.93	$11,162.93
175	$34,696.60	$11,748.33
200	$36,944.80	$12,931.60
250	$43,262.33	$13,969.07
300	$47,491.20	
400	$58,948.93	
500	$66,970.53	
600	$79,661.07	
700	$87,406.47	
750	$91,254.40	
800	$95,079.53	
900	$108,849.67	
1000	$116,644.87	
1100	$124,159.40	
1250	$140,941.13	
1500	$159,627.00	
1645	$170,409.33	

Capital Cos	Metals Precipitation											
Metals	pH = 2						pH = 6					
Influent	Heavy Metals Concentration											
flow, GPM	0.5	1	5	50	500	1000	0.5	1	5	50	500	1000
1	$105,778	$105,778	$105,778	$105,778	$105,778	$105,778	$105,778	$105,778	$105,778	$105,778	$105,778	$105,778
5	$106,027	$106,027	$106,027	$106,027	$106,027	$106,027	$106,027	$106,027	$106,027	$106,027	$106,027	$106,027
10	$108,938	$108,938	$108,938	$108,938	$108,938	$108,938	$108,938	$108,938	$108,938	$108,938	$108,938	$108,938
25	$126,272	$126,272	$126,272	$126,272	$126,272	$126,272	$126,272	$126,272	$126,272	$126,272	$126,272	$126,272
50	$188,157	$188,157	$188,157	$188,157	$188,157	$188,157	$188,157	$188,157	$188,157	$188,157	$188,157	$188,157
75	$238,079	$238,079	$238,079	$238,079	$238,079	$238,079	$238,079	$238,079	$238,079	$238,079	$238,079	$238,079
100	$240,303	$240,303	$240,303	$240,303	$240,303	$240,303	$240,303	$240,303	$240,303	$240,303	$240,303	$240,303

O & M Cost	Metals Precipitation											
Metals	pH = 2						pH = 6					
Influent	Heavy Metals Concentration											
flow, GPM	0.5	1	5	50	500	1000	0.5	1	5	50	500	1000
1	$162,756	$164,756	$164,756	$165,077	$165,717	$166,358	$162,515	$162,515	$162,515	$162,515	$163,155	$164,116
5	$216,416					$224,422						
10	$258,958					$274,971						
25	$372,118					$412,792						
50	$569,339					$650,687						
75	$741,242					$863,583						
100	$849,256	$849,256	$849,896	$857,262	$930,603	$1,012,271	$596,246	$596,246	$596,887	$604,253	$677,914	$759,581

Total Cost	Metals Precipitation											
Metals	pH = 2						pH = 6					
Influent	Heavy Metals Concentration											
flow, GPM	0.5	1	5	50	500	1000	0.5	1	5	50	500	1000
1	$268,534	$270,534	$270,534	$270,855	$271,495	$272,136	$268,293	$268,293	$268,293	$268,293	$268,933	$269,894
5	$322,443					$330,449						
10	$367,896					$383,909						
25	$498,390					$539,064						
50	$757,496					$838,844						
75	$979,321					$1,101,662						
100	$1,089,559	$1,089,559	$1,090,199	$1,097,565	$1,170,906	$1,252,574	$836,549	$836,549	$837,190	$844,556	$918,217	$999,884

Annual O&	Metals Precipitation											
Metals	pH = 2						pH = 6					
Influent	Heavy Metals Concentration											
flow, GPM	0.5	1	5	50	500	1000	0.5	1	5	50	500	1000
1	$10,850.40	$10,983.73	$10,983.73	$11,005.13	$11,047.80	$11,090.53	$10,834.33	$10,834.33	$10,834.33	$10,834.33	$10,877.00	$10,941.07
5	$14,427.73	$0.00	$0.00	$0.00	$0.00	$14,961.47	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
10	$17,263.87	$0.00	$0.00	$0.00	$0.00	$18,331.40	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
25	$24,807.87	$0.00	$0.00	$0.00	$0.00	$27,519.47	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
50	$37,955.93	$0.00	$0.00	$0.00	$0.00	$43,379.13	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
75	$49,416.13	$0.00	$0.00	$0.00	$0.00	$57,572.20	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
100	$56,617.07	$56,617.07	$56,659.73	$57,150.80	$62,040.20	$67,484.73	$39,749.73	$39,749.73	$39,792.47	$40,283.53	$45,194.27	$50,638.73

Capital Cos Metals Influent flow, GPM	pH = 7 0.5	1	5	50	500	1000	pH = 8 0.5	1	5	50	500	1000
1	$105,778	$105,778	$105,778	$105,778	$105,778	$105,778	$105,778	$105,778	$105,778	$105,778	$105,778	$105,778
5	$106,027	$106,027	$106,027	$106,027	$106,027	$106,027	$106,027	$106,027	$106,027	$106,027	$106,027	$106,027
10	$108,938	$108,938	$108,938	$108,938	$108,938	$108,938	$108,938	$108,938	$108,938	$108,938	$108,938	$108,938
25	$126,272	$126,272	$126,272	$126,272	$126,272	$126,272	$126,272	$126,272	$126,272	$126,272	$126,272	$126,272
50	$188,157	$188,157	$188,157	$188,157	$188,157	$188,157	$188,157	$188,157	$188,157	$188,157	$188,157	$188,157
75	$238,079	$238,079	$238,079	$238,079	$238,079	$238,079	$238,079	$238,079	$238,079	$238,079	$238,079	$238,079
100	$240,303	$240,303	$240,303	$240,303	$240,303	$240,303	$240,303	$240,303	$240,303	$240,303	$240,303	$240,303

O & M Cost Metals Influent flow, GPM	pH = 7 0.5	1	5	50	500	1000	pH = 8 0.5	1	5	50	500	1000
1	$162,515	$162,515	$162,515	$162,515	$162,515	$162,515	$162,515	$162,515	$162,515	$162,515	$162,515	$162,515
5	$203,925	$203,925	$203,925	$203,925	$203,925	$203,925				$203,639		
10	$233,657	$233,657	$233,657	$233,657	$233,657	$233,657				$233,085		
25	$309,346	$309,346	$309,346	$309,346	$309,346	$309,346				$307,631		
50	$443,795	$443,795	$443,795	$443,795	$443,795	$443,795				$440,078		
75	$553,246	$553,246	$553,246	$553,246	$553,246	$553,246				$547,527		
100	$598,488	$598,488	$598,488	$598,488	$598,488	$598,488	$590,768	$590,768	$590,768	$590,768	$590,768	$590,768

Total Cost Metals Influent flow, GPM	pH = 7 0.5	1	5	50	500	1000	pH = 8 0.5	1	5	50	500	1000
1	$268,293	$268,293	$268,293	$268,293	$268,293	$268,293	$268,293	$268,293	$268,293	$268,293	$268,293	$268,293
5	$309,952	$309,952	$309,952	$309,952	$309,952	$309,952				$309,666		
10	$342,595	$342,595	$342,595	$342,595	$342,595	$342,595				$342,023		
25	$435,618	$435,618	$435,618	$435,618	$435,618	$435,618				$433,903		
50	$631,952	$631,952	$631,952	$631,952	$631,952	$631,952				$628,235		
75	$791,325	$791,325	$791,325	$791,325	$791,325	$791,325				$785,606		
100	$838,791	$838,791	$838,791	$838,791	$838,791	$838,791	$831,071	$831,071	$831,071	$831,071	$831,071	$831,071

Annual O& Metals Influent flow, GPM	pH = 7 0.5	1	5	50	500	1000	pH = 8 0.5	1	5	50	500	1000
1	$10,834.33	$10,834.33	$10,834.33	$10,834.33	$10,834.33	$10,834.33	$10,834.33	$10,834.33	$10,834.33	$10,834.33	$10,834.33	$10,834.33
5	$13,595.00	$13,595.00	$13,595.00	$13,595.00	$13,595.00	$13,595.00	$0.00	$0.00	$0.00	$13,575.93	$0.00	$0.00
10	$15,577.13	$15,577.13	$15,577.13	$15,577.13	$15,577.13	$15,577.13	$0.00	$0.00	$0.00	$15,539.00	$0.00	$0.00
25	$20,623.07	$20,623.07	$20,623.07	$20,623.07	$20,623.07	$20,623.07	$0.00	$0.00	$0.00	$20,508.73	$0.00	$0.00
50	$29,586.33	$29,586.33	$29,586.33	$29,586.33	$29,586.33	$29,586.33	$0.00	$0.00	$0.00	$29,338.53	$0.00	$0.00
75	$36,883.07	$36,883.07	$36,883.07	$36,883.07	$36,883.07	$36,883.07	$0.00	$0.00	$0.00	$36,501.80	$0.00	$0.00
100	$39,899.20	$39,899.20	$39,899.20	$39,899.20	$39,899.20	$39,899.20	$39,384.53	$39,384.53	$39,384.53	$39,384.53	$39,384.53	$39,384.53

Capital Cos

Metals Influent flow, GPM	pH = 12 0.5	1	5	50	500	1000
1	$105,778	$105,778	$105,778	$105,778	$105,778	$105,778
5	$106,027	$106,027	$106,027	$106,027	$106,027	$106,027
10	$108,938	$108,938	$108,938	$108,938	$108,938	$108,938
25	$126,272	$126,272	$126,272	$126,272	$126,272	$126,272
50	$188,157	$188,157	$188,157	$188,157	$188,157	$188,157
75	$238,079	$238,079	$238,079	$238,079	$238,079	$238,079
100	$240,303	$240,303	$240,303	$240,303	$240,303	$240,303

O & M Cost

Metals Influent flow, GPM	pH = 12 0.5	1	5	50	500	1000
1	$163,086	$163,086	$163,086	$163,086	$163,086	$163,086
5						
10						
25						
50						
75						
100	$669,968	$669,968	$669,968	$669,968	$669,968	$669,968

Total Cost

Metals Influent flow, GPM	pH = 12 0.5	1	5	50	500	1000
1	$268,864	$268,864	$268,864	$268,864	$268,864	$268,864
5						
10						
25						
50						
75						
100	$910,271	$910,271	$910,271	$910,271	$910,271	$910,271

Annual O&

Metals Influent flow, GPM	pH = 12 0.5	1	5	50	500	1000
1	$10,872.40	$10,872.40	$10,872.40	$10,872.40	$10,872.40	$10,872.40
5	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
10	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
25	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
50	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
75	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
100	$44,664.53	$44,664.53	$44,664.53	$44,664.53	$44,664.53	$44,664.53

Appendix F. Summary of Technologies for Ordnance

Safety Level D Capital Ordnance	Bioreactor COD (ppm) 50	500	1000	Advanced Oxidation Processes TNT Influent Conc./Effluent Conc. (mg/L) 0.1/0.02	1/0.02	5/0.02	10/0.02	100/0.02	1000/0.02	RDX Nitrobenzen TNB	GAC Single Pass Dual Bed	Disposable
1	$71,979	$71,979	$96,896	N/A	N/A	N/A	N/A	N/A	N/A	N/A	$40,361	$1,811
5	$71,979	$71,979	$96,896	$100,389	$109,296	$109,296	$109,296	$115,934	$122,715	$115,672	$40,361	$1,811
10	$72,457	$97,375	$146,831	$109,296	$115,934	$122,715	$122,715	$136,296	$143,058	$115,672	$40,361	$2,011
25	$152,640	$164,123	$207,571	$118,049	$145,173	$158,792	$165,608	$192,652	$220,019	$208,141	$41,325	$4,033
50	$211,593	$211,698	$304,089	$142,489	$196,729	$224,096	$237,683	$305,864	$334,119	$212,218	$42,367	$7,924
100	$271,007	$325,230	N/A	$191,185	$279,752	$342,223	$381,936	N/A	N/A	$220,323	$43,777	$13,180
150	N/A	N/A	N/A	$223,202	$386,670	N/A	N/A	N/A	N/A	$334,978	$103,882	$21,770
200	N/A	N/A	N/A	$290,181	$459,772	N/A	N/A	N/A	N/A	$340,674	$104,274	$22,162
250	N/A	N/A	N/A	$333,514	N/A	N/A	N/A	N/A	N/A	$349,791	$107,587	N/A
500	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	$162,839	N/A
750	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	$306,129	N/A
1000	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	$307,046	N/A
1500	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	$462,240	N/A
2000	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	$466,185	N/A
2250	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

Safety Level D O&M 15 Year Ordnance	Bioreactor COD (ppm) 50	500	1000	Advanced Oxidation Processes TNT Influent Conc./Effluent Conc. (mg/L) 0.1/0.02	1/0.02	5/0.02	10/0.02	100/0.02	1000/0.02	DNT HMX RDX Nitrobenzen TNB	GAC Single Pass Dual Bed	Disposable
1	$120,175	$120,175	$148,212	N/A	N/A	N/A	N/A	N/A	N/A	N/A	$64,773	$27,756
5	$212,467	$212,467	$240,504	$295,772	$337,844	$359,346	$369,893	$409,410	$446,830	$273,831	$88,122	$76,514
10	$309,449	$337,486	$393,134	$456,436	$528,002	$580,897	$599,730	$679,109	$748,556	$375,296	$110,559	$130,946
25	$669,425	$682,347	$731,234	$892,527	$1,083,290	$1,208,384	$1,264,268	$1,454,941	$1,643,719	$755,798	$170,769	$287,641
50	$1,158,313	$1,158,432	$1,262,390	$1,618,241	$1,997,500	$2,250,092	$2,361,810	$2,769,178	$3,121,082	$1,220,500	$264,722	$543,615
100	$2,026,311	$2,087,322	N/A	$3,042,995	$3,792,284	$4,311,445	$4,547,482	N/A	N/A	$2,125,638	$436,312	$1,037,182
150	N/A	N/A	N/A	$4,444,998	$5,599,052	N/A	N/A	N/A	N/A	$3,144,426	$668,191	$1,528,747
200	N/A	N/A	N/A	$5,887,835	$7,359,100	N/A	N/A	N/A	N/A	$4,031,941	$834,202	$2,012,406
250	N/A	N/A	N/A	$7,295,340	N/A	N/A	N/A	N/A	N/A	$4,924,369	$998,248	N/A
500	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	$1,849,776	N/A
750	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	$2,794,650	N/A
1000	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	$3,570,867	N/A
1500	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	$5,291,275	N/A
2000	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	$6,835,382	N/A
2250	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

Safety Level C Total Ordnance	Bioreactor COD (ppm) 50	500	1000	Advanced Oxidation Processes TNT Influent Conc./Effluent Conc. (mg/L) 0.1/0.02	1/0.02	5/0.02	10/0.02	100/0.02	1000/0.02	RDX Nitrobenzen TNB	GAC Single Pass Dual Bed	Disposable
1	$192,154	$192,154	$245,108	N/A	N/A	N/A	N/A	N/A	N/A	N/A	$105,134	$29,567
5	$284,446	$284,446	$337,400	$396,161	$447,140	$468,642	$479,189	$525,344	$569,545	$389,503	$128,483	$78,325
10	$381,906	$434,861	$539,965	$565,732	$643,936	$703,612	$722,445	$815,405	$891,614	$490,968	$150,920	$132,957
25	$822,065	$846,470	$938,805	$1,010,576	$1,228,463	$1,367,176	$1,429,876	$1,647,593	$1,863,738	$963,939	$212,094	$291,674
50	$1,369,906	$1,370,130	$1,566,479	$1,760,730	$2,194,229	$2,474,188	$2,599,493	$3,075,042	$3,455,201	$1,432,718	$307,089	$551,539
100	$2,297,318	$2,412,552	N/A	$3,234,180	$4,072,036	$4,653,668	$4,929,418	N/A	N/A	$2,345,961	$480,089	$1,050,362
150	N/A	N/A	N/A	$4,668,200	$5,985,722	N/A	N/A	N/A	N/A	$3,479,404	$772,073	$1,550,517
200	N/A	N/A	N/A	$6,178,016	$7,818,872	N/A	N/A	N/A	N/A	$4,372,615	$938,476	$2,034,568
250	N/A	N/A	N/A	$7,628,854	N/A	N/A	N/A	N/A	N/A	$5,274,160	$1,105,835	N/A
500	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	$2,012,615	N/A
750	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	$3,100,779	N/A
1000	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	$3,877,913	N/A
1500	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	$5,753,515	N/A
2000	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	$7,301,567	N/A
2250	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

Safety Level C Annual O & M Ordnance	Bioreactor COD (ppm) 50	500	1000	Advanced Oxidation Processes TNT Influent Conc./Effluent Conc. (mg/L) 0.1/0.02	1/0.02	5/0.02	10/0.02	100/0.02	1000/0.02	DNT HMX RDX Nitrobenzen TNB	GAC Single Pass Dual Bed	Disposable
1	$8,011.67	$8,011.67	$9,880.80	N/A	N/A	N/A	N/A	N/A	N/A	N/A	$4,318.20	$1,850.40
5	$14,164.47	$14,164.47	$16,033.60	$19,718.13	$22,522.93	$23,956.40	$24,659.53	$27,294.00	$29,788.67	$18,255.40	$5,874.80	$5,100.93
10	$20,629.93	$22,499.07	$26,208.93	$30,429.07	$35,200.13	$38,726.47	$39,982.00	$45,273.93	$49,903.73	$25,019.73	$7,370.60	$8,729.73
25	$44,628.33	$45,489.80	$48,748.93	$59,501.80	$72,219.33	$80,558.93	$84,284.53	$96,996.07	$109,581.27	$50,386.53	$11,384.60	$19,176.07
50	$77,220.87	$77,228.80	$84,159.33	$107,882.73	$133,166.67	$150,006.13	$157,454.00	$184,611.87	$208,072.13	$81,366.67	$17,648.13	$36,241.00
100	$135,087.40	$139,154.80	N/A	$202,866.33	$252,818.93	$287,429.67	$303,165.47	N/A	N/A	$141,709.20	$29,087.47	$69,145.47
150	N/A	N/A	N/A	$296,333.20	$373,270.13	N/A	N/A	N/A	N/A	$209,628.40	$44,546.07	$101,916.47
200	N/A	N/A	N/A	$392,522.33	$490,606.67	N/A	N/A	N/A	N/A	$268,796.07	$55,613.47	$134,160.40
250	N/A	N/A	N/A	$486,356.00	N/A	N/A	N/A	N/A	N/A	$328,291.27	$66,549.87	N/A
500	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	$123,318.40	N/A
750	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	$186,310.00	N/A
1000	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	$238,057.80	N/A
1500	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	$352,751.67	N/A
2000	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	$455,692.13	N/A
2250	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

Safety Level D Capital Ordnance	GAC 2 in Series Dual Bed	 Disposable	Media Filtration
1	$79,447	$2,346	$14,310
5	$79,447	$2,346	$14,310
10	$79,447	$2,746	$14,310
25	$80,411	$5,828	$14,471
50	$81,453	$12,566	$23,606
100	$82,862	$21,669	$33,895
150	$201,385	$37,162	$44,897
200	$201,777	$37,554	$50,086
250	$205,091	N/A	$50,196
500	$311,368	N/A	N/A
750	$603,188	N/A	N/A
1000	$604,105	N/A	N/A
1500	$907,829	N/A	N/A
2000	$911,774	N/A	N/A
2250	N/A	N/A	N/A

Safety Level D O&M 15 Year Ordnance	GAC 2 in Series Dual Bed	 Disposable	Media Filtration
1	$108,752	$28,358	$32,560
5	$132,101	$77,116	$44,063
10	$154,538	$131,773	$52,266
25	$214,749	$289,660	$68,111
50	$308,701	$548,839	$98,733
100	$480,291	$1,046,734	$135,693
150	$777,902	$1,546,066	$167,444
200	$943,913	$2,029,725	$193,974
250	$1,107,958	N/A	$209,536
500	$2,016,901	N/A	N/A
750	$3,128,901	N/A	N/A
1000	$3,905,118	N/A	N/A
1500	$5,792,652	N/A	N/A
2000	$7,336,759	N/A	N/A
2250	N/A	N/A	N/A

Safety Level C Total Ordnance	GAC 2 in Series Dual Bed	Disposable	Media Filtration
1	$188,199	$30,704	$46,870
5	$211,548	$79,462	$58,373
10	$233,985	$134,519	$66,576
25	$295,160	$295,488	$82,582
50	$390,154	$561,405	$122,339
100	$563,153	$1,068,403	$169,588
150	$979,287	$1,583,228	$212,341
200	$1,145,690	$2,067,279	$244,060
250	$1,313,049	N/A	$259,732
500	$2,328,269	N/A	N/A
750	$3,732,089	N/A	N/A
1000	$4,509,223	N/A	N/A
1500	$6,700,481	N/A	N/A
2000	$8,248,533	N/A	N/A
2250	N/A	N/A	N/A

Safety Level C Annual O & M Ordnance	GAC 2 In Series Dual Bed	Disposable	Media Filtration
1	$7,250.13	$1,890.53	$2,170.67
5	$8,806.73	$5,141.07	$2,937.53
10	$10,302.53	$8,784.87	$3,484.40
25	$14,316.60	$19,310.67	$4,540.73
50	$20,580.07	$36,589.27	$6,582.20
100	$32,019.40	$69,782.27	$9,046.20
150	$51,860.13	$103,071.07	$11,162.93
200	$62,927.53	$135,315.00	$12,931.60
250	$73,863.87	N/A	$13,969.07
500	$134,460.07	N/A	N/A
750	$208,593.40	N/A	N/A
1000	$260,341.20	N/A	N/A
1500	$386,176.80	N/A	N/A
2000	$489,117.27	N/A	N/A
2250	N/A	N/A	N/A

Appendix G. Testing and Analysis Costs

	Unit Cost				
VOC					
Purgeable Aromatics (SW 5030/SW 8020), Water Analysis	$96.67 ea				
Purgeable Halocarbons (SW 5030/SW 8010), Water Analysis	$121.67 ea				
		VOC	$c^{ana,\ water}$	=	$218.34
Tentative ID Compounds, GC/MS, (30/5040/8620 - TO - 14), Air A	$260.00 ea				
		VOC	$c^{ana,\ gas}$	=	$260.00
SVOC					
Base Neutral & Acid Extractable Organics (SW 3510/SW8270), W	$434.67 ea				
		SVOC	$c^{ana,\ water}$	=	$434.67
Semivolatiles, Air (TO - 13), Air Analysis	$520.00 ea				
		SVOC	$c^{ana,\ gas}$	=	$520.00
Fuels					
BTEX/MTBE/TVPH (EPA 8020/8015 Mod) Water Analysis	$105.00 ea				
Total Dissolved Solids (EPA 160.1), Water Analysis	$12.00 ea				
Total Suspended Solids (EPA 160.2), Water Analysis	$10.15 ea				
Total Petroleum Hydrocarbons (SW 8015), Water Analysis	$66.67 ea				
Ethylene Disbromide (EDB) (EPA 501.4)	$78.33 ea				
Polynuclear Aromatic Hydrocarbons, PAH (SW 3510/SW 8310),	$188.33 ea				
		Fuels	$c^{ana,\ water}$	=	$460.48
Hydrocarbon Speciation, C1-C22, GC/FID, Air (TO - 12/14)	$75.00 ea				
		Fuels	$c^{ana,\ gas}$	=	$75.00
Metals					
TAL Metals (EPA 6010/7000s), Water Analysis	$305.00 ea				
Total Suspended Solids (EPA 160.2), Water Analysis	$10.15 ea				
Total Dissolved Solids (EPA 160.1), Water Analysis	$12.00 ea				
		Metals	$c^{ana,\ water}$	=	$327.15
Ordnance					
EPA Method 8330 (11 Compounds) Nitroaromatics/Nitramines	$297.41 ea				
		Ordnance	$c^{ana,\ water}$	=	$297.41

Bibliography

Culver, T. B. and Shoemaker, C. A. (1997), "Dynamic Optimal Ground-Water Reclamation with Treatment Capital Costs", *Journal of Water Resources Planning and Management*, ASCE, 123(1), 23-29

Freeze, R.A., and Cherry, J. A. (1979), *Groundwater*, Prentice-Hall, Inc., Englewood Cliffs, N.J.

Minsker, B. S. and Shoemaker C. A. (1998), "Dynamic Optimal Control of In-Situ Bioremediation of Ground Water", *Journal of Water Resources Planning and Management*, ASCE, 124(3), 149-161

"RACER 99: Remedial Action Cost Engineering and Requirements Users Guide" Talisman Partners, Ltd., 1999

Smalley, J. B. (1992), "Risk-Based In Situ Bioremediation Design", MS thesis, Department of Civil and Environmental Engineering, University of Illinois, Urbana-Champaign, IL

U.S. Environmental Protection Agency (1996), "Cleaning Up the Nation's Waste Sites", EPA/542/R-96/005A

U.S. Environmental Protection Agency (1996), "Pump-and-Treat Groundwater Remediation: Guide for Decision Makers and Practitioners", EPA/625/R-95/005, Office of Research and Development National Risk Management Research Laboratory Center for Environmental Research Information Cincinnati, Ohio

U.S. Environmental Protection Agency (1997), "Remediation Technologies Screening Matrix and Reference Guide", 3rd Edition, Federal Remediation Technologies Roundtable